THORLABS

In collaboration with

BOSTON MICROMACHINES CORPORATION

AOK5(/M), AOK8(/M), AOKWT1(/M) Adaptive Optics Kits

User Guide

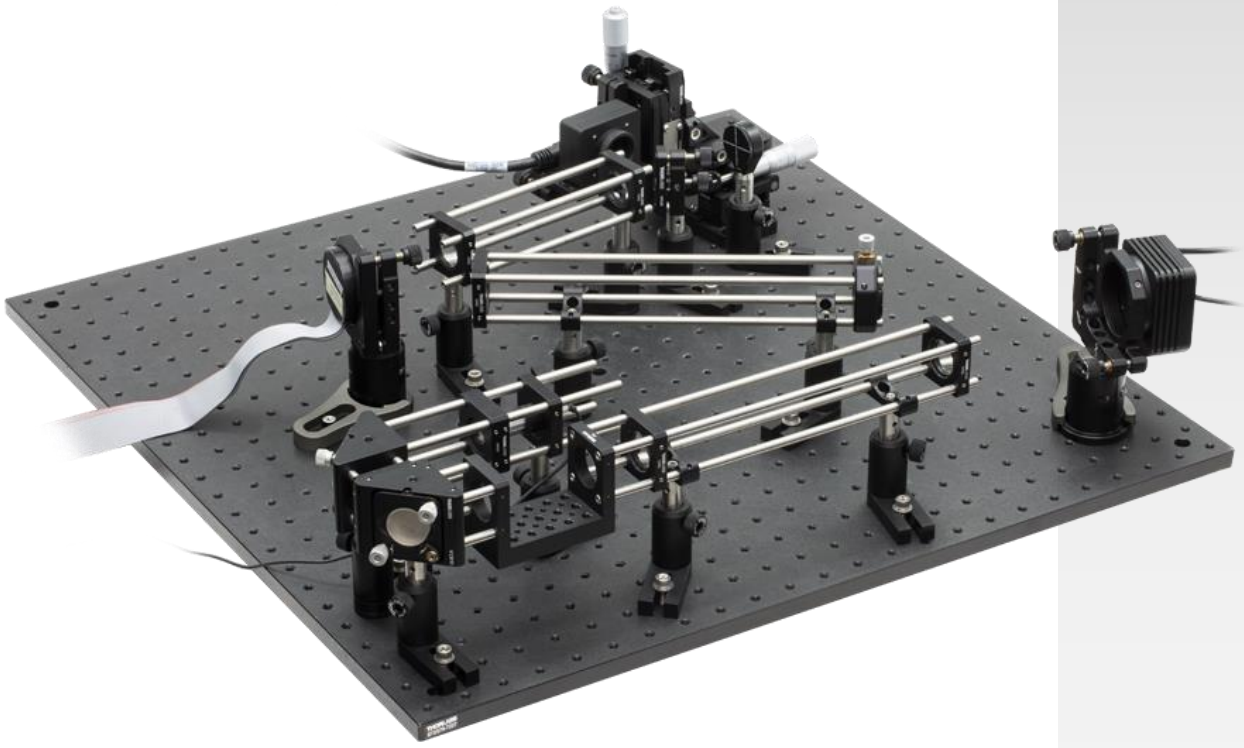


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Chapter 1 Warning Symbol Definitions

Below is a list of warning symbols you may encounter in this manual or on your device.

Symbol	Description
	Direct Current
	Alternating Current
	Both Direct and Alternating Current
	Earth Ground Terminal
	Protective Conductor Terminal
	Frame or chassis Terminal
	Equipotentiality
	On (Supply)
	Off (Supply)
	In Position of a Bi-Stable Push Control
	Out Position of a Bi-Stable Push Control
	Caution, Risk of Electric Shock
	Caution, Hot Surface
	Caution, Risk of Danger
	Warning, Laser Radiation
	Caution, Spinning Blades May Cause Harm

Chapter 2 Safety

ATTENTION USERS

Please read the instruction manual carefully before operating the Adaptive Optics Kit System. All statements regarding safety and technical specifications will only apply when the unit is operated correctly.

This equipment is intended for laboratory use only and is not certified for medical applications, including but not limited to life support situations.

ATTENTION

This device can only be returned when received in the complete original packaging, including all parts and foam packing inserts. If necessary, ask for replacement packing materials.

HIGH VOLTAGE WARNING!

Before applying power to your system, make sure that the protective conductor of the 3 conductor main power cord is correctly connected to the protective earth contact of the socket outlet. Improper grounding can cause electric shock resulting in severe injury or even death!

Shock Hazard: Voltages up to 300 V can be present on the deformable mirror (DM), packaging, electrodes, cable, or electronics driver.

LASER RADIATION WARNING!

Do not, under any circumstances, look into the optical output when the device is operating.

Specific System Classification for Laser Module Output: Class 1 @ 635 nm

ELECTROSTATIC DISCHARGE (ESD) WARNING

All types of electronic components, particularly integrated circuits, are sensitive to Electrostatic Discharge (ESD). ESD can lead to electronic equipment failure. The total operating time may be reduced if precautions against ESD damage are not taken.

ALWAYS wear an ESD wrist strap connected to an ESD terminal whenever handling the Adaptive Optics Toolkit (see Figure 1). One is included with the DM.

DM Damage

The DM is highly sensitive to electrostatic discharge. Always wear a Grounding Wrist Strap when handling the DM in an electrostatically sensitive environment. Avoid touching the electrodes on the backside of the DM.

Multi-Driver Damage

The Driver is also highly sensitive to electrostatic discharge. Always wear a Grounding Wrist Strap when handling the Driver in an electro statically sensitive environment. Avoid touching any electrical interconnects.

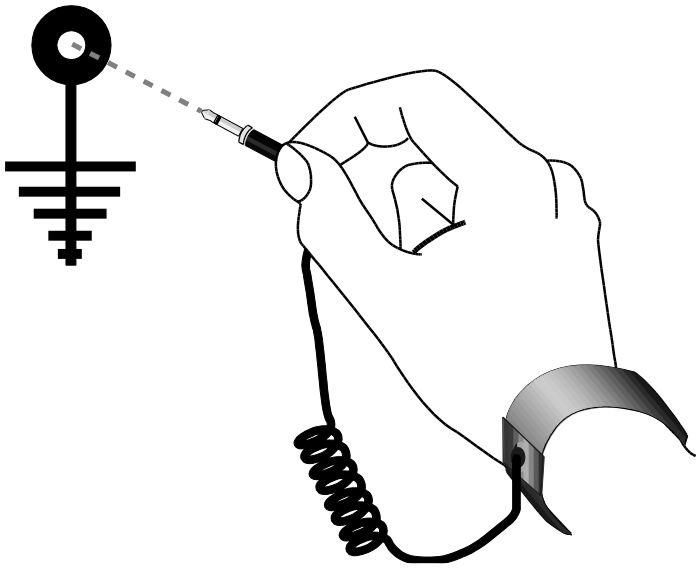


Figure 1 ESD Wrist Wrap

Chapter 3 Description

Adaptive optics (AO) has been a rapidly growing multidisciplinary field encompassing physics, chemistry, electronics, and computer science. AO systems are used to correct (shape) the wavefront of a beam of light. Historically, these systems have their roots in the international astronomy and US defense communities. Astronomers realized that if they could compensate for the aberrations caused by atmospheric turbulence, they would be able to generate high-resolution astronomical images. More recently, due to advancements in the sophistication and simplicity of AO components, researchers have utilized these systems to make breakthroughs in the areas of femtosecond pulse shaping, microscopy, laser communication, vision correction, and retinal imaging. Although these are dramatically different fields, they all benefit from the ability of AO systems to compensate for undesirable time-varying effects.

Typically, an AO system is comprised of three components: (1) a wavefront sensor, which measures optical wavefront deviations, (2) a deformable mirror, which can change shape in order to modify a distorted optical wavefront, and (3) real-time control software, which uses the information collected by the wavefront sensor to calculate the appropriate shape that the deformable mirror should assume in order to compensate for the distorted wavefront. These three components operate together as a closed loop system by automatically detecting and compensating for any changes in the optical wavefront. In principle, this closed-loop system is quite simple; it measures the phase as a function of position across the optical wavefront under consideration, computes a correction to achieve the desired wavefront, reshapes the deformable mirror, observes the consequence of the correction, and then repeats this process as necessary if the phase aberration varies with time. Via this procedure, the AO system can improve the optical resolution of an image by removing aberrations from the wavefront of the light being imaged.

3.1. System Description

Thorlabs provides a series of AO toolkits capable of real-time wavefront compensation through the implementation of a closed loop system incorporating a Shack-Hartmann Wavefront Sensor, a deformable mirror (DM), and control software created for this purpose. In addition to the AO kits based on either a single MEMS based deformable mirror from Boston Micromachines Corporation (BMC), the leading developer of MEMS-based mirrors, or a single Thorlabs bimorph piezoelectric DM, the new Thorlabs AO system application allows for woofer-tweeter AO systems. In a woofer-tweeter AO system, two deformable mirrors are used in conjugate planes, such that one mirror (a woofer) corrects for lower order aberrations and the other, the tweeter, corrects higher order aberrations. For example, in one setup of woofer-tweeter AO systems, the Thorlabs bimorph DM, which includes 40 segments for deforming the mirror surface, arranged in a pie/keystone configuration conducive for lower order Zernike modal control, is used as the woofer, while the BMC Multi-DM is used as the tweeter.

Our closed-loop control AO system includes a Shack-Hartmann Wavefront Sensor (Item # WFS20, WFS30 or WFS40), which measures wavefront aberrations, Thorlabs' bimorph DM or BMC's Mini- / Multi- MEMS deformable mirror, which can change shape in order to modify an optical wavefront, and real-time control software, which uses the information collected by the wavefront sensor to calculate the required shape for the deformable mirror to compensate for aberrations. Together, these three components operate in a closed-loop configuration with a frame rate dependent upon the wavefront sensor and control algorithm.

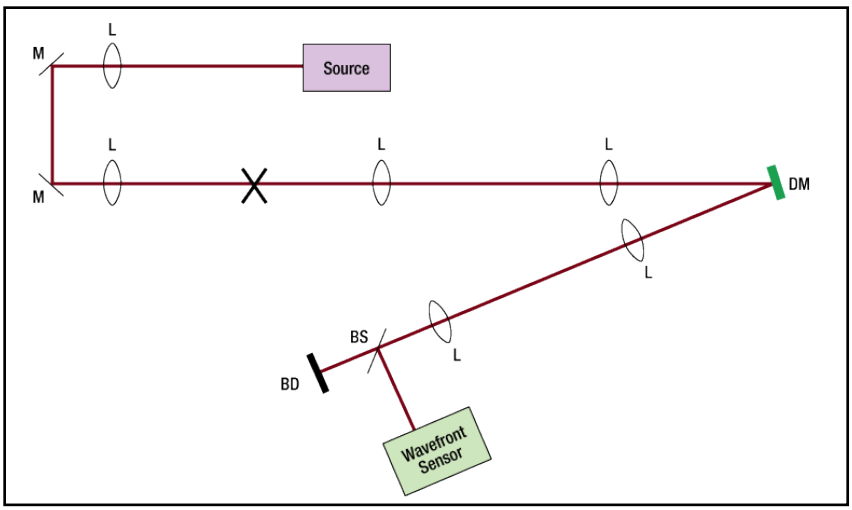


Figure 2 The schematic above shows the major components included with a typical single-DM, Single-WFS kit. L, M, DM, BS, and BD refer to lens, mirror, deformable mirror, beam splitter, and beam dump, respectively. The X denotes the location of a plane conjugate to the DM and WFS, where the user can insert a sample.

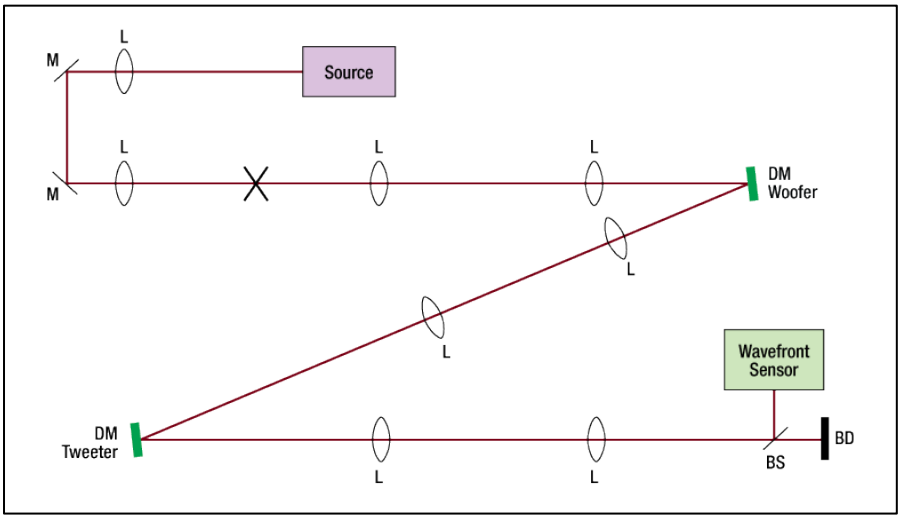


Figure 3 Sample AO Kit Woofer-Tweeter Schematic Showing the Major Components with Two DMs and a Single WFS kit. L, M, DM, BS, and BD refer to lens, mirror, deformable mirror, beam splitter, and beam dump, respectively. The X denotes the location of a plane conjugate to both DMs and WFS, where the user can insert a sample.

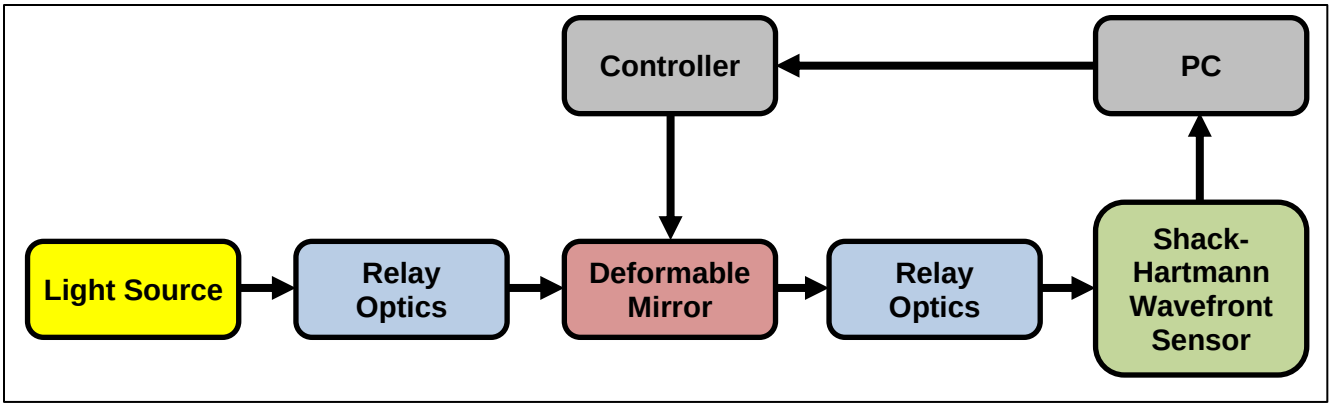


Figure 4 AO Kit Block Diagram System Description

3.2. Shack-Hartmann Wavefront Sensor

Each of Thorlabs' AO kits includes either a WFS20-5C, WFS30-5C or WFS40-5C Shack-Hartmann wavefront sensor. These instruments enable accurate, high-speed measurements of the wavefront shape and intensity distribution of a beam of light. Each wavefront sensor is equipped with a chrome mask microlens array (Thorlabs part number MLA150-5C) that is AR coated for the 300 nm to 1100 nm range. This microlens array images the far-field wavefront of a beam onto a CMOS camera chip, forming a spot field that provides information about the beam's wavefront. This makes it possible to characterize the aberrations introduced by optical components and provide real-time feedback for the control of a deformable mirror.

Each kit includes a WFS20-5C Fast Shack-Hartmann Wavefront Sensor, which incorporates a CMOS camera capable of providing frame rates as high as 880 fps. An SM1-threaded interface adapter is provided for the convenient mounting of ND filters, which help prevent camera saturation, and lens tubes, which reduce scattered light and provide the ability to mount additional optical components. The SM1-threaded interface may be removed in order to interface with C-Mount components.



Figure 5 Fast Shack-Hartmann Wavefront Sensor WFS20-5C

3.3. Deformable Mirror

3.3.1 Bimorph Deformable Mirror

Thorlabs' Bimorph Piezoelectric Deformable Mirror (DM) complements the BMC MEMS-based DM. The silver-coated mirror is designed for use with light in the 450 nm to 20 µm wavelength range and is available in two styles. One style includes three (3) independent bimorph piezoelectric arms to adjust for tip and tilt. This style has a Ø10 mm pupil and a Ø11.5 mm aperture and piezoelectric segment design enabling a wavefront phase correction of up to ±13.6 µm (astigmatism). The second style is a high-stroke version that has a Ø14 mm pupil and a Ø17 mm aperture and piezoelectric segment design enabling a wavefront phase correction of up to ±36.8 µm (astigmatism). Both DMs are ideal for correcting distortions that result from common sources of wavefront aberrations, such as defocus, astigmatism and coma. Please see the full specifications on page 149 for more details.



Figure 6 Thorlabs' DMH40-P01 Bimorph Mirror

3.3.2 MEMS Deformable Mirror

Micro-electro-mechanical (MEMS) deformable mirrors (DM) are currently the most widely used instruments in wavefront shaping applications due to the versatility and maturity of the underlying technology and the high-resolution wavefront correction they provide. Thorlabs' popular and versatile Multi-DM offers sophisticated aberration compensation in an easy-to-use package. These mirrors consist of a continuous mirror surface that is deformed by 140 electrostatic actuators (a 12 x 12 actuator array with four inactive corner actuators), each of which can be individually controlled. These actuators provide 3.5 µm of stroke over a compact area with little influence on neighboring actuators. Unlike piezoelectric-actuated mirrors, BMC's electrostatic-actuated mirrors deform without hysteresis. Each deformable mirror incorporates a window with a 6° wedge to protect the mirror. The window has a broadband AR coating for the 400 nm to 1100 nm range. For more information on specific kits, see Chapter 11.



Figure 7 BMC's DM140A-35-Ux01 MEMS Deformable Mirror Modules

3.4 Control Software

Note, the Control Software is explained in detail in Chapter 5 of this manual.

The control software provided with the adaptive optics kit has been redesigned “from the ground up”. The earlier version of the AO Kit application started as a demo-application to help users become familiar with what was capable when using our wavefront sensors and BMC's Mini- and Multi-DMs in a closed loop control system. Over the years the application was modified to add functionality and to be compatible with new Thorlabs wavefront sensors and the introduction of our piezo-based deformable mirrors. Redesigning the AO Kit application allowed for the addition of functionality asked for by users, as well as functionality we felt was missing based on internal use. It now includes full functional support of the Thorlabs wavefront sensor functionality.

Key Features of the New Control Application:

1) Plugin-module-based code design allows expansion of functionality without requiring the application to be upgraded to newer versions.
    a. BMC Mini- / Multi- deformable mirrors
    b. Thorlabs piezo-based deformable mirror family
    c. Thorlabs wavefront sensor family – now with full functional support
    d. Control processors
2) Additional control methods:
    a. Basic 1 DM / 1 WFS closed loop control with a “poke” calibration method,
        i. Modal calibration and control for our DMH40 or DMP40 deformable mirrors
        ii. Zonal calibration and control for the BMC Mini- and Multi-deformable mirrors.
    b. Three methods for closed loop woofer-tweeter calibration and control.
        i. Sequential Independent mirror control
        ii. Dual mirror response matrix orthogonalization
        iii. Dual mirror Lagrange-multiplier least-squares matrix
3) Multiple user-defined systems assigned per user profiles

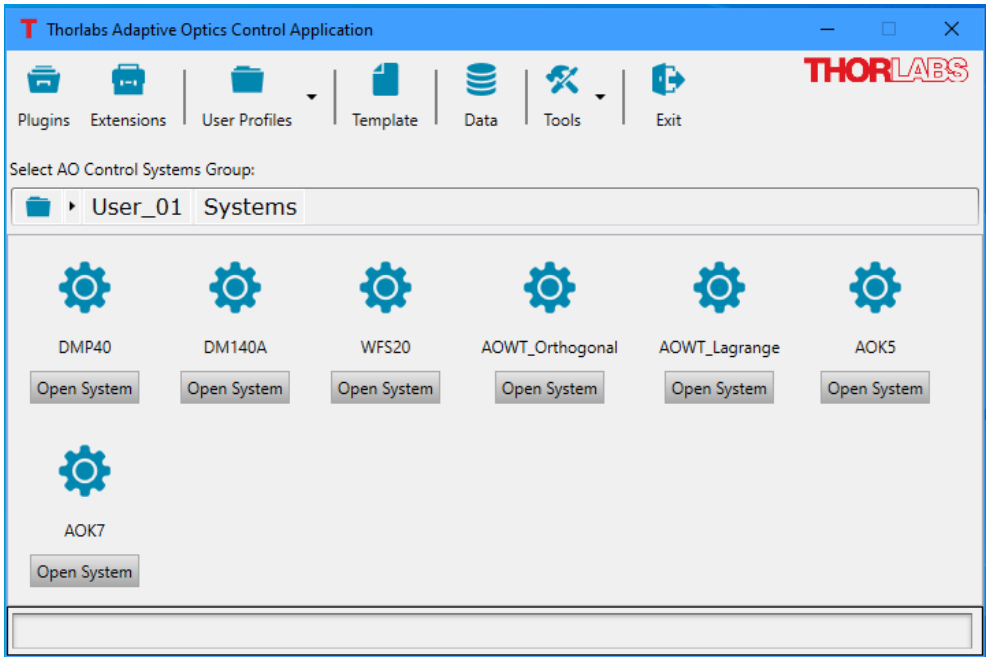


Figure 8 Software Main Window Display

3.5 Requirements

Here are some requirements for running the Thorlabs AO Control Software.

3.5.1 Hardware Requirements

- Display Resolution: Minimum 1280 x 1024 pixels is recommended
- USB Interface: When using a Thorlabs wavefront sensor in the system, a USB 1.1 full speed port is not sufficient. For best performance, USB 2.0 or USB 3.0 port is recommended for a **WFS20 sensor head**; USB 3.0 port is recommended for a **WFS30 or WFS40 sensor head**.

Please refer to the individual manual for specific requirements for an individual device.

3.5.2 Software Requirements

The Thorlabs AO Control Software is compatible with the following operating systems:

- Windows® 7 SP1 (32-bit, 64-bit)
- Windows® 8.1 (32-bit, 64-bit)
- Windows® 10 (32-bit, 64-bit)

For running the Thorlabs AO Control Software, .Net Framework 4.5 (or higher) must be installed.

Chapter 4 System Assembly and Installation

4.1. Software Installation

ATTENTION

Please install software prior to connecting the instruments to your PC via the USB interface. This will ensure that the correct drivers will be found.

The AO Control Software Installation requires Microsoft .NET 4.5 framework. If the software is not installed already on the host computer, the installation software will install it during setup.

1. Insert the ThorAOControl Application Software USB drive into an available USB port.
2. Run “ThorAOKit_Setup.exe” from \Setup folder. A setup window is displayed as shown in Figure 9.
3. In addition to the ThorAOControl application, the Thorlabs Wavefront Sensor (WFS), the Thorlabs piezo-based Deformable Mirror and / or the Boston Micromachines MEMS-based Deformable Mirror drivers need to be installed to run the ThorAOControl application.
4. The installation of Thorlabs Wavefront Sensor driver and Thorlabs Deformable Mirror driver may require the restart of the computer. After the restart of the computer, the installation of Thorlabs Wavefront Sensor driver and Thorlabs Deformable Mirror driver will resume. Wait until the installation finishes, then Run “ThorAOKit_Setup.exe” from \Setup folder again.
5. After the installation of the Boston MicroMachines Deformable Mirror driver, user needs to copy the device-specific files to the proper locations. The device-specific files include Deformable Mirror Profile (.dm) and the Flat Map Commands file.
6. Once the setup is complete, a new desktop shortcut will be placed on your desktop, as shown in Figure 10. The software can now be started by double clicking the ThorAOControl App icon on the desktop.
7. The AO Control Software can also be started by accessing the application from the Windows Start button.

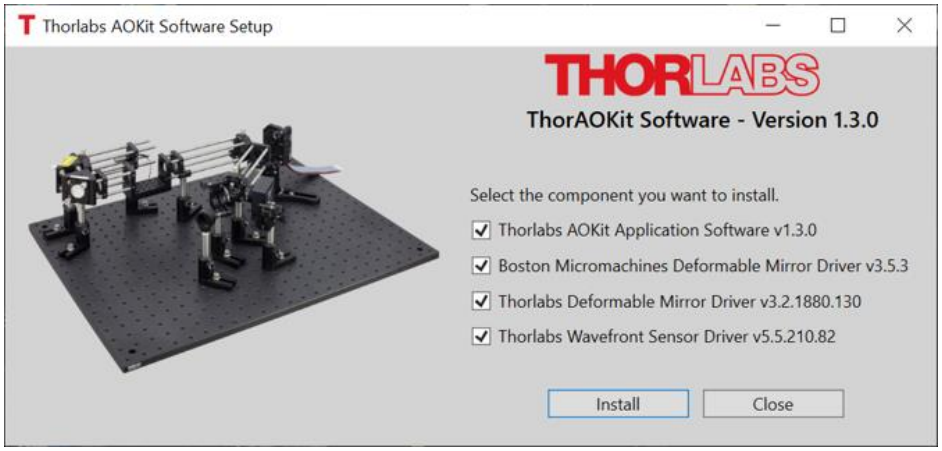


Figure 9 ThorAOKit Software Installation



Figure 10 Icon Installed on Desktop

By default, 64-bit application and components are installed in the following directories.

1. **Program executable and library files (DLLs)** are stored in:

   C:\Program Files\Thorlabs\ThorAOControl

2. **Application default user profile** is stored in folder:

   C:\Program Files\Thorlabs\ThorAOControl\Application

3. **Display assemblies used in the program** are stored in folder:

   C:\Program Files\Thorlabs\ThorAOControl\DisplayAssemblies

4. **Documentations** are stored in folder

   C:\Program Files\Thorlabs\ThorAOControl\Documentation

5. **Sample projects** is stored in folder

   C:\Program Files\Thorlabs\ThorAOControl\Examples

6. **Extension modules and Extension UI modules** are stored in folder:

   C:\Program Files\Thorlabs\ThorAOControl\Extensions

7. **Plugin modules and Plugin UI modules** are stored in folder:

   C:\Program Files\Thorlabs\ThorAOControl\Plugins

8. **SDK files** are stored in folder

   C:\Program Files\Thorlabs\ThorAOControl\SDK

9. **Files recorded by the user** are saved to folder:

   C:\Users\[user_name]\Documents\Thorlabs\ThorAOControl\[UserProfile_Name]\[ControlGroup_Name]\[ControlSystem_Name]

10. **Application active configurations, AO layout templates and User Profile files** are stored in folder:

    C:\Users\[user_name]\AppData\Roaming\Thorlabs\ThorAOControl

11. **Other Files generated by the program that do not get updated by the program** are stored in folder:

    C:\Users\[user_name]\AppData\Roaming\Thorlabs\ThorAOControl

32-bit application and components are also available. Please contact Thorlabs Technical Support at **techsupport@thorlabs.com** for more information.

4.2. Shack-Hartmann Connection

ATTENTION

The Wavefront Sensor will not work on a full speed USB 1.1 port!

Be sure to connect the wavefront sensor to a high-speed USB 2.0 or USB 3.0 port. Do NOT use cables that are not explicitly suited for high-speed USB data transfer, as this can cause transmission errors and improper instrument operation!

To connect the Shack-Hartmann Wavefront Sensor, follow the steps below:

1. Find the USB 2.0 / 3.0 high speed USB Type-A to Mini USB Type-B cable included with your kit.
2. Insert the Mini USB Type-B connection into the corresponding port at the back of the Shack-Hartmann Sensor
3. Connect the USB Type-A cable into one of the applicable slots available on your computer.

Important Note

After the Shack-Hartmann is plugged in, the computer should find the new hardware and install the driver that has just been installed from the ThorAOControl Application Software USB Drive. Once the new hardware is found, there should be a green light on the back of the Shack-Hartmann to let you know that it is properly recognized by the system.

4.3. Deformable Mirror Connection

4.3.1. Piezo Electric Deformable Mirror (DMH40 or DMP40) Connections

For the following steps, please refer to the figures below:

1. Connect one end of the supplied USB cable to the USB Mini connection on the side of the DMH40 or DMP40 head.
2. Connect the other end of the USB cable (end A) into one of the USB slots available on your computer or powered USB hub.
3. Plug in the DMH40 or DMP40 power supply then connect the DC plug on the power supply shipped with the DM into the power supply input on the DM head.



Figure 11 Piezo Electric Deformable Mirror (DMP40 shown) Connections

4.3.2. MEMS Deformable Mirror (DM140A-35-x01) Connections

For the following steps, please refer to the figures below:

1. Connect the USB cable to the front panel of the DM driver unit.
2. Connect the other end of the USB cable (end A) into one of the USB slots available on your computer.
3. Plug in the DB-37 ribbon cable(s) from of the rear of the DM Module into the appropriate receptacle on the back of the drive unit. Note that the multi-driver module has four cables labeled J1 to J4.
4. If you are setting up the multi-driver module, insert the power supply cord into the power input at the rear panel and plug the other end into the appropriate 110/230 VAC wall outlet.

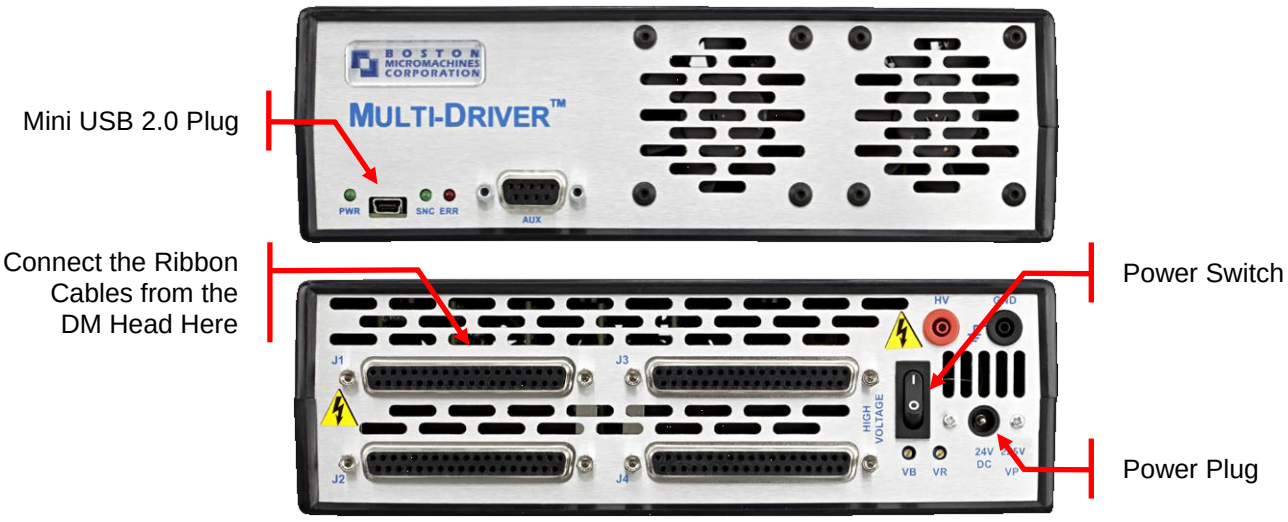


Figure 12 DM Multi Drive Control Unit

After the Deformable Mirror is plugged in, the computer should find the new hardware and install the driver that has just been installed from the USB.

4.4. Deformable Mirror Mounting (Bimorph Piezoelectric)

ATTENTION

The mirror surface is Protected Silver and does not include a protective window. The mirror coating can be damaged by using improper cleaning techniques and direct contact.
Do NOT touch the mirror surface.

1. Remove the protective cap covering the front of the Deformable Mirror.
2. Thread the SM2AB1 onto the SM2 threads on the mirror side of the Deformable Mirror. Reference Figure 13.
3. Insert and secure the RS1.5P8 (RS38P4/M) post into the RSH2(/M) post holder using a 3/16" ball driver or hex key.
4. Secure the KS2D kinematic mount to the RS1.5P8 (RS38P4/M) using the 8-32 socket head cap screw provided.
5. Insert and secure the SM2AB1 into the KS2D kinematic mount with the bottom of the DMP40-P01 or DMH40-P01 parallel with the bottom mounting surface of the KS2D mount. Secure the SM2AB1 in position by tightening the socket head setscrew in the KS2D mount using a 5/64 ball driver or hex key.



Figure 13 Deformable Mirror Assembly

4.5. Deformable Mirror Mounting (Multi-DM with Cylindrical Housing)

ATTENTION

An ESD wrist strap should always be worn while handling the DM or drive electronics. Always handle the mirror in a statically sensitive manner by using a grounded wrist strap and avoiding contact with the electrodes.

A window with an anti-reflective (AR) coating is mounted over the mirror; this is to control humidity exposure and contamination. Do NOT touch the window. AR coatings can be damaged by using improper cleaning techniques.

1. Remove the protective plastic tab covering the part on the front of the Deformable Mirror housing.
2. Secure the KS2D to the RS1.5P8 (RS38P4/M) post using the provided socket head cap screw.
3. Insert the RS1.5P8 (RS38P4/M) post into the RSH2(/M) post holder and secure it using the locking screw on the RSH2(/M). Fine alignment can be achieved when the setup is placed on the desired breadboard or table.
4. Insert the DM housing into the KS2D and secure it in position by tightening the nylon tipped setscrew shown in the figure to the right.
5. Adjust the position of the RS1.5P8 (RS38P4/M) in the RSH2(/M) such that the center of the DM is nominally at height of 113 mm.



Figure 14 Deformable Mirror Assembly

4.6. Shack-Hartmann and Beamsplitter Assembly

The following instructions detail mounting the Shack-Hartmann sensor for the single DM kits (see Figure 15 below).

1. Secure the KM100WFS to the TR2 (TR50/M) post using an 8-32 (M4) screw, and then place the post into the UPH2 (UPH50/M) post holder.
2. Using the screws included with the KM100WFS, mount the WFS40-5C(/M) or WFS20-5C(/M) to the KM100WFS platform. The WFS40 models use one 8-32 (M4) screw and the WFS20 models use two 8-32 (M4) screws as shown in the figure below.

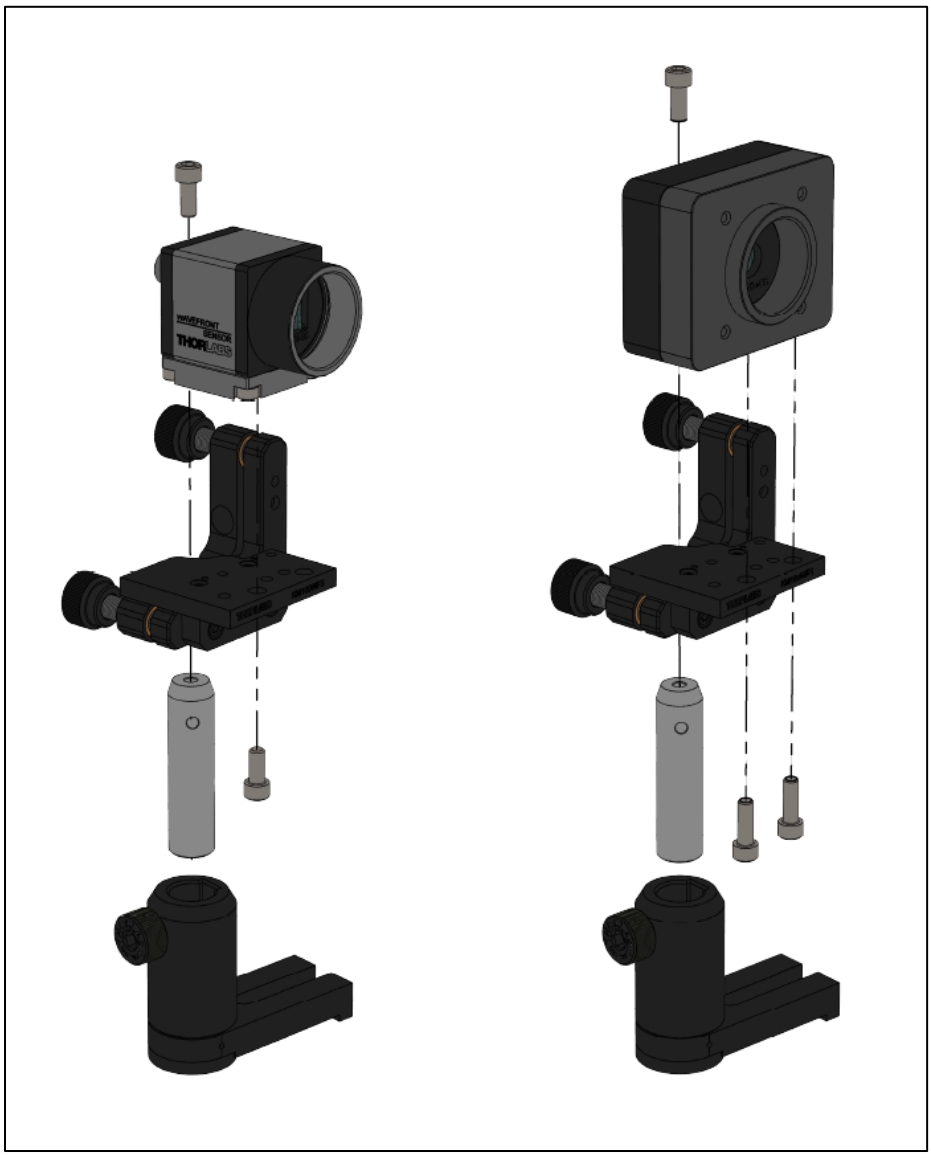


Figure 15 ***Shack-Hartmann Wavefront Sensor Mounting Assembly, WFS40 shown on left, WFS20 shown on right.***

The following instructions detail mounting the Shack-Hartmann sensor for the woofer-tweeter kits (see Figure 17 below):

Step 1. Assemble the XYZ Stage

1. Secure XRN-YZ(/M) Plate to one of the three XRN25P(/M) Stages by sliding the plate dovetail into the underside of the stage. Secure by tightening the 1/4"-20 (M6) screw on the stage.
2. Secure the stage and plate assembly to one of the XRN-YZ(/M) Bracket by sliding the stage dovetail onto the Z-axis of the bracket. Secure by tightening the 1/4"-20 (M6) screw on Z-axis of the bracket.
3. Secure the stage, plate, and bracket assembly onto the second XRN25P(/M) Bracket by sliding the Y-axis of the bracket onto the top of the stage. Secure by tightening the 1/4"-20 (M6) screw on Y-axis of the bracket.
4. Secure the assembly onto the third XRN25P(/M) by sliding the dovetail into the bottom of the second (y-axis) stage of the bracket onto the top of the third stage (x-axis). Secure by tightening the 1/4"-20 (M6) screw on the second stage.
5. Secure the XYZ assembly onto the stage base, XRN-B1, by sliding the bottom stage onto the base dovetail. Secure by tightening the 1/4"-20 (M6) screw on Y-axis of the bracket.

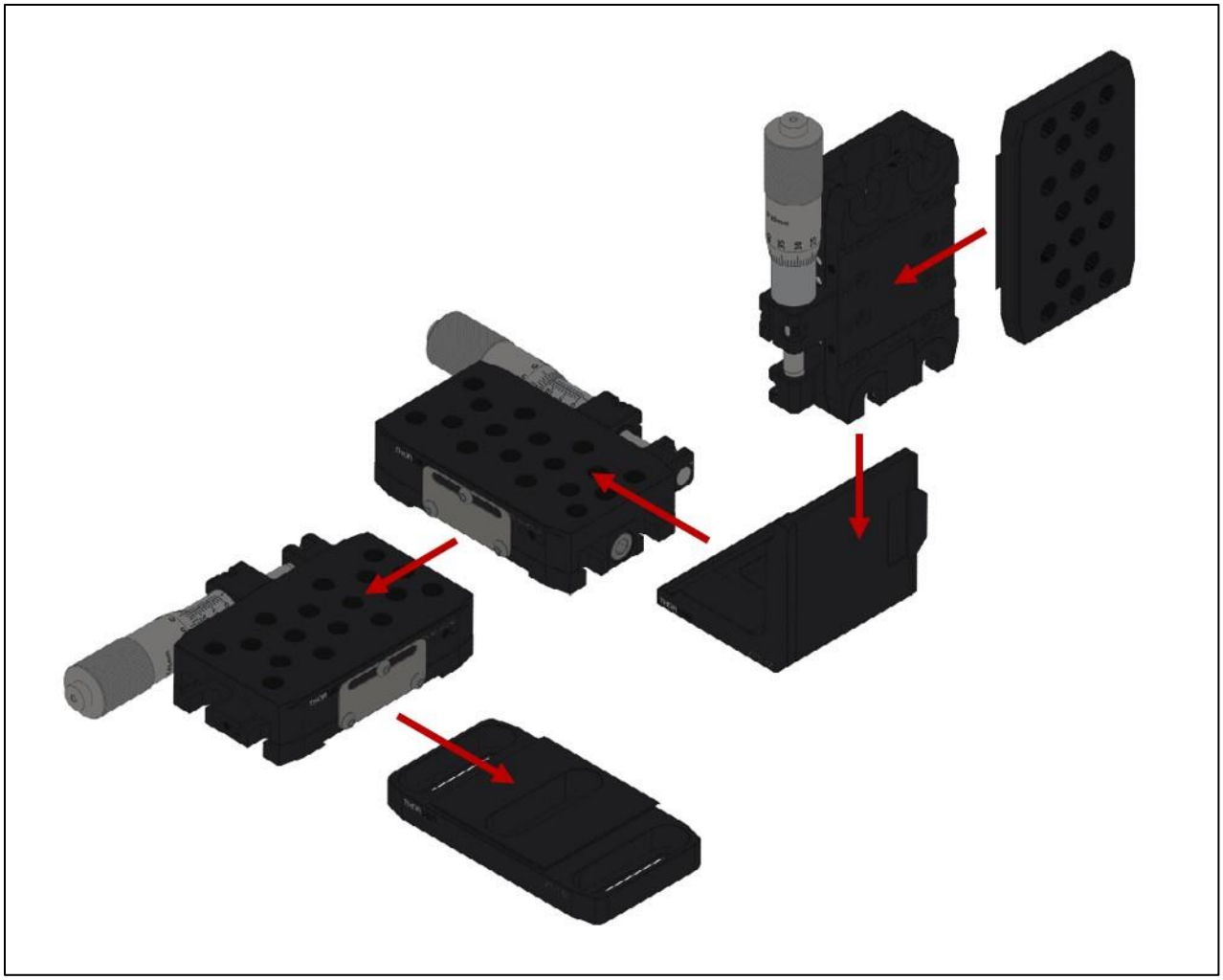


Figure 16 XYZ Stage Assembly – assembly order starts from the top right

Step 2. Mount the Shack-Hartmann sensor on the kinematic mount and install on the XYZ stage:

1. Install the thread adapter, AE8E25ES (AE4M6MS), into the z-axis stage XRN25P(/M), as shown in the figure below.
2. Attach the WFS20-5C(/M) to the KM200PM with two 8-32 (M4) screws.
3. Secure the KM200PM to the XRN25P(/M) using a one 8-32 (M4) screws into the AE8E25ES (AE4M6MS).

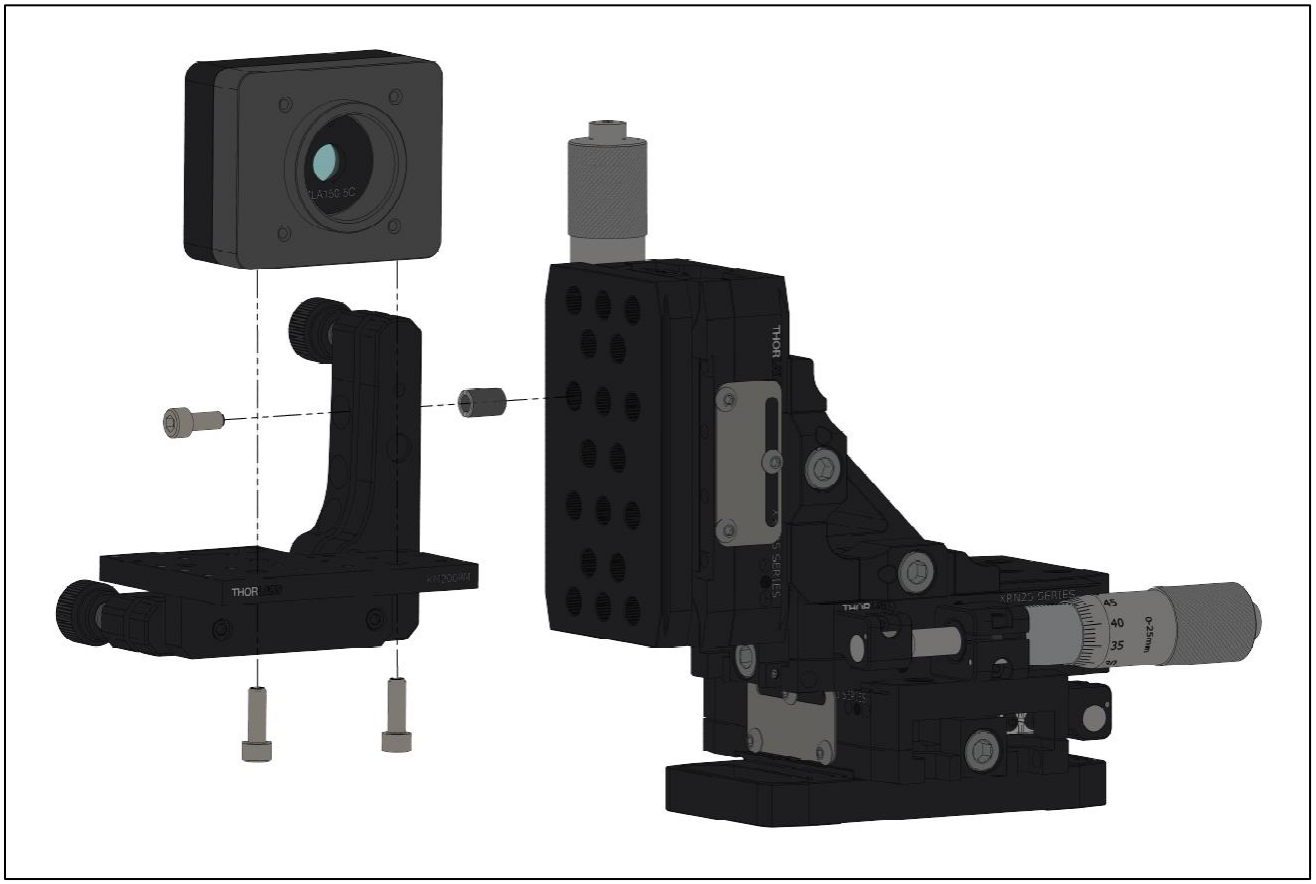


Figure 17 Shack-Hartmann Assembly Procedure

4.7. Beamsplitter and Alignment Plate Assembly

Next, follow the instructions to assemble the single DM kits that include a pellicle beam splitter and the alignment plate that is included in all kits (see Figure 17 below):

1. Screw the BP108 pellicle beamsplitter into the KM100BP mount using the two supplied screws. **Note:** The pellicle beamsplitters are extremely fragile; do NOT touch the thin surface membrane or the beamsplitter will be destroyed!
2. Secure the mount to the TR2 (TR50/M) post with an SH8S025-1 (SH4MS06-1) screw and insert the post into a UPH2 (UPH50/M) post holder.
3. Screw the SM1A7 alignment plate into the LMR1(/M). The retaining ring inside the LMR1(/M) may be used to secure the alignment plate with the crosshairs located at the desired orientation. Attach the LMR1(/M) to the TR2 (TR50/M) post and insert the post into a UPH2 (UPH50/M) post holder.

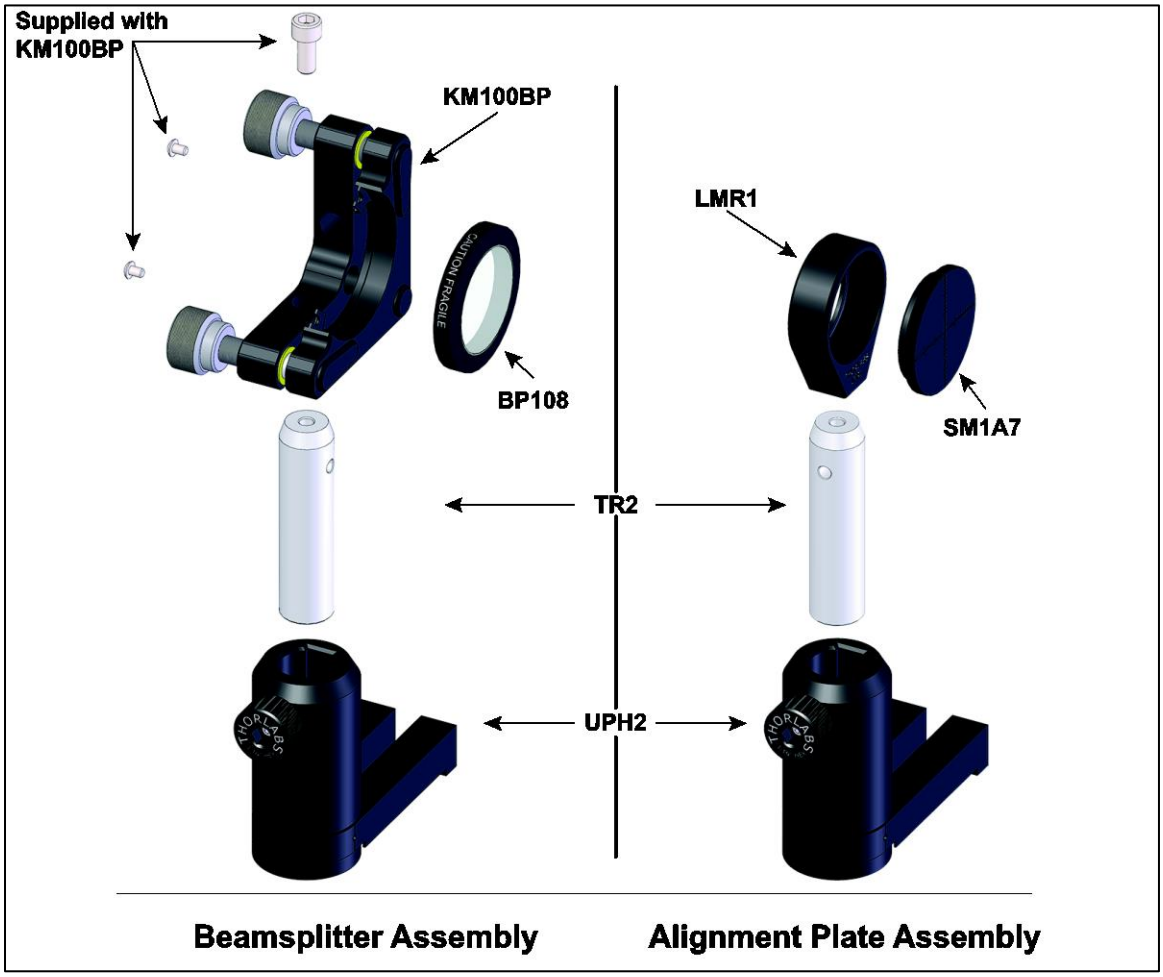


Figure 18 Beamsplitter and Alignment Plate Assembly Procedure

The following instructions detail mounting the Plate Beamsplitter included with the Woofer-Tweeter Kits (see Figure 19 below).

1. Screw the BSN10 plate beamsplitter into the KM100 and secure it in position by tightening the nylon tipped setscrew. Ensure the arrow engraved on the BSN10 edge pointing towards the kinematic mount actuators.
2. Secure the mount to the TR2 (TR50/M) post with an SH8S025-1 (SH4MS06-1) screw and insert the post into a UPH2 (UPH50/M) post holder.

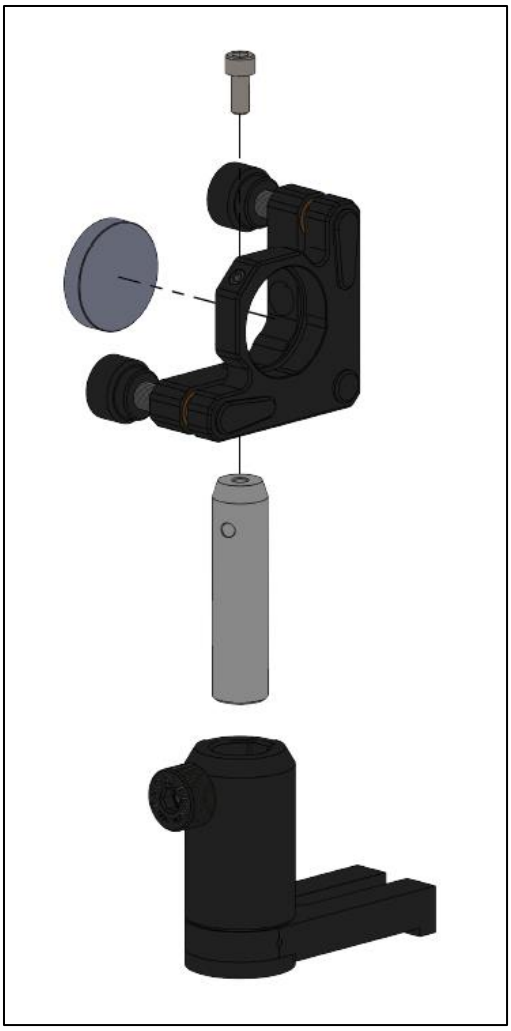


Figure 19 Plate Beamsplitter with Kinematic Mount Assembly

4.8. Adaptive Optics Kit Assembly

Thorlabs offers AO Kits that include one Thorlabs piezoelectric based DM, one BMC Multi-DM, or one of each DM.

The AO Kits that include one DM have five distinct subassemblies: the deformable mirror (subassembly 3), three preassembled cage sections that contain the necessary optical elements (subassemblies 1, 2, and 4), and the wavefront sensor, beamsplitter, and beam dump (subassembly 5). The optical elements of subassemblies 1 and 2 are pre-aligned such that the planar wavefront at the output of the laser will be imaged onto the sample plane (i.e. within the location of the CBB1(/M)) and the location the DM surface is to be aligned when the full kit is assembled. Subassembly 4 is a pre-aligned 4-f optical relay. The DM is positioned at the input focal plane of the first lens and the lenslet array of the Shack-Hartman sensor is positioned at the output of the second lens when the full kit is assembled. Mounting posts and bases are included with the AO Kit to allow the system to be assembled on a breadboard or an optical table. Figure 20 shows the five subassemblies of the kit and how these subassemblies are integrated to form the completed single DM system.

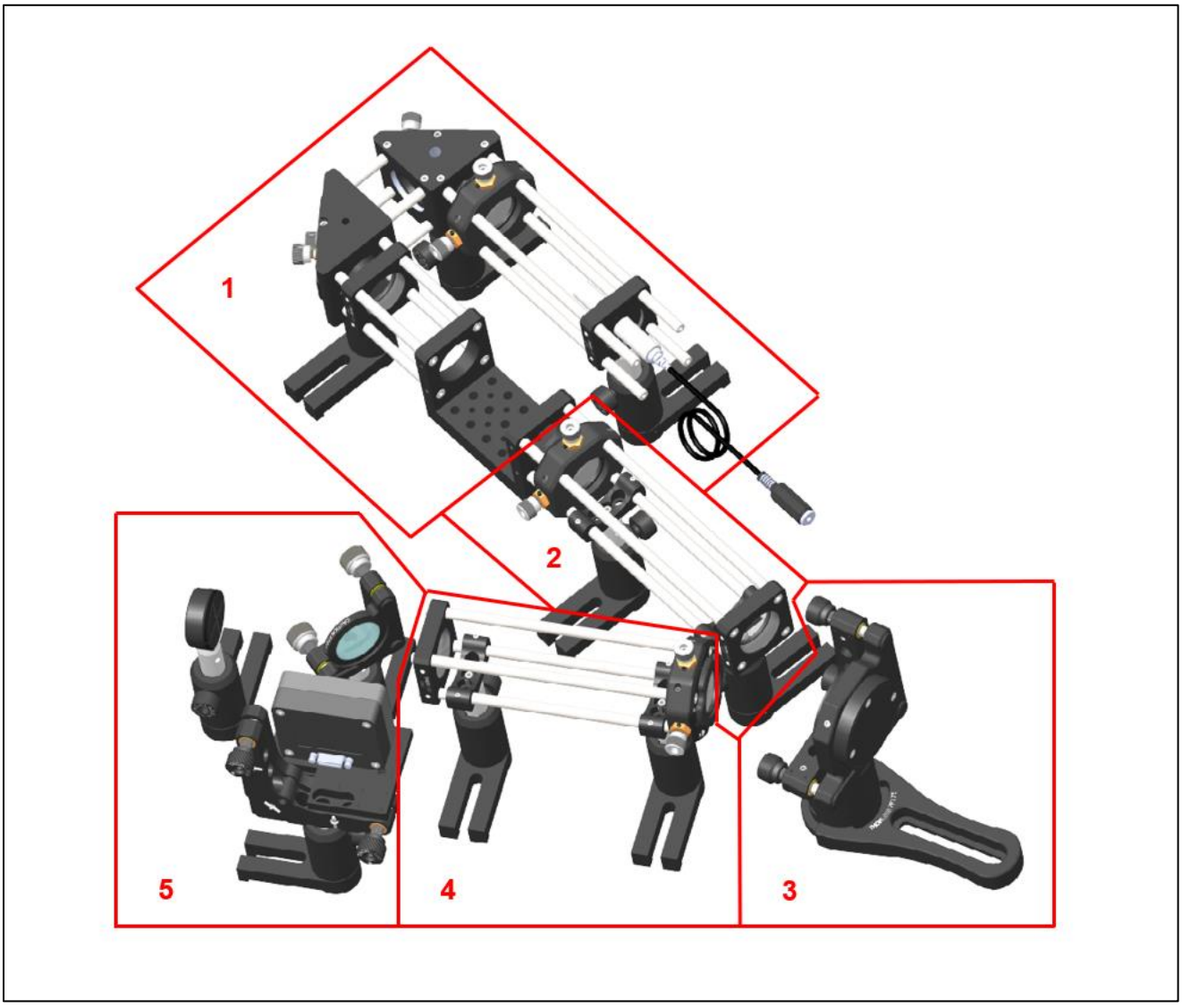


Figure 20 Representative Single DM AO Kit (AOK5 Components Shown)

Subassembly	Qty.	AOK5(/M) Item #	Qty.	AOK8(/M) Item #
1	1	635 nm Laser Diode Module, 0.30 mW	1	635 nm Laser Diode Module, 0.30 mW
	1	LA1131-B	1	LA1289-B
	1	LA1608-B	1	LA1509-B
	2	PF10-03-P01	2	PF10-03-P01
	1	CBB1(/M)	1	CBB1(/M)
	1	KCB1(/M)	1	KCB1(/M)
	1	KCB1C(/M)	1	KCB1C(/M)
	1	CXY1A	1	CP33T
	2	CP33(/M)	2	CP33(/M)
			1	AD1T
	3	TR2 (TR50/M)	3	TR2 (TR50/M)
	3	UPH2 (UPH50/M)	3	UPH2 (UPH50/M)
	1	AD11F	1	AD11F
	4	ER05	4	ER1
	4	ER2	4	ER1.5
	4	ER6	4	ER6
2	2	LA1608-B	1	LA1433-B
	1	CXY1A	1	LA1608-B
	1	CP33(/M)	2	CP33(/M)
	2	CP33B	2	CP33B
	2	TR2 (TR50/M)	2	TR2 (TR50/M)
	2	UPH2 (UPH50/M)	2	UPH2 (UPH50/M)
	4	ER2	4	ER3
	4	ER6	4	ER8
3	1	DM140A-35-P01	1	DMH40-P01 (DMH40/M-P01)
	1	PF125B	1	PF125B
	1	RS1.5P8 (RS38P4/M)	1	RS1.5P8 (RS38P4/M)
	1	RSH2(/M)	1	RSH2(/M)
	1	KS2D	1	KS2D
			1	SM2AB1
4	2	LA1608-B	1	LA1134-B
			1	LA1229-B
	1	CXY1A	1	CXY1A
	1	CP33(/M)	1	CP33(/M)
	2	CP33B	2	CP33B
	2	TR2 (TR50/M)	2	TR2 (TR50/M)
	2	UPH2 (UPH50/M)	2	UPH2 (UPH50/M)
	4	ER05	4	ER10
	4	ER6		
5	1	NE10A	1	NE10A
	1	NE20A	1	NE20A
	1	BP108	1	BP108

Subassembly	Qty.	AOK5(/M) Item #	Qty.	AOK8(/M) Item #
5	1	LMR1(/M)	1	LMR1(/M)
	1	SM1A7	1	SM1A7
	1	SM1A9	1	SM1A9
	1	WFS20-5C(/M)	1	WFS20-5C(/M)
	1	KM100BP	1	KM100BP
	1	KM200PM(/M)	1	KM200PM(/M)
	3	TR2 (TR50/M)	1	TR1.5 (TR40/M)
			2	TR2 (TR50/M)
	3	UPH2 (UPH50/M)	1	UPH1.5 (UPH40/M)
			2	UPH2 (UPH50/M)
Not Shown	3	CPA1	3	CPA1
Not Shown	1	CPSA	1	CPSA
Not Shown	1	DS5	1	DS5

Note: The above table is for the AOK5(/M) and AOK8(/M) kits. For the packing list, see Chapter 11.1

The AO Kits that include two DMs, woofer-tweeter configurations, have seven distinct subassemblies: the woofer deformable mirror (subassembly 3), the tweeter deformable mirror (subassembly 5), four preassembled cage sections that contain the necessary optical elements (subassemblies 1, 2, 4, and 6), and the wavefront sensor, beamsplitter, and beam dump (subassembly 7). The optical elements of subassemblies 1, 2, and 4 are pre-aligned such that the planar wavefront at the output of the laser will be imaged onto the sample plane (i.e. within the location of the CBB1(/M)) and the location the DMs surfaces are to be aligned when the full kit is assembled. Subassembly 6 is a pre-aligned 4-f optical relay. The tweeter DM is positioned at the input focal plane of the first lens and the lenslet array of the Shack-Hartman sensor is positioned at the output focal plane of the second lens when the full kit is assembled. Mounting posts and bases are included with the AO Kit to allow the system to be assembled on a breadboard or an optical table. Below is a description of the constituent components for each of the five subassemblies that form the AO kit system. Figure 21 shows how these subassemblies are integrated to form the completed single DM system.

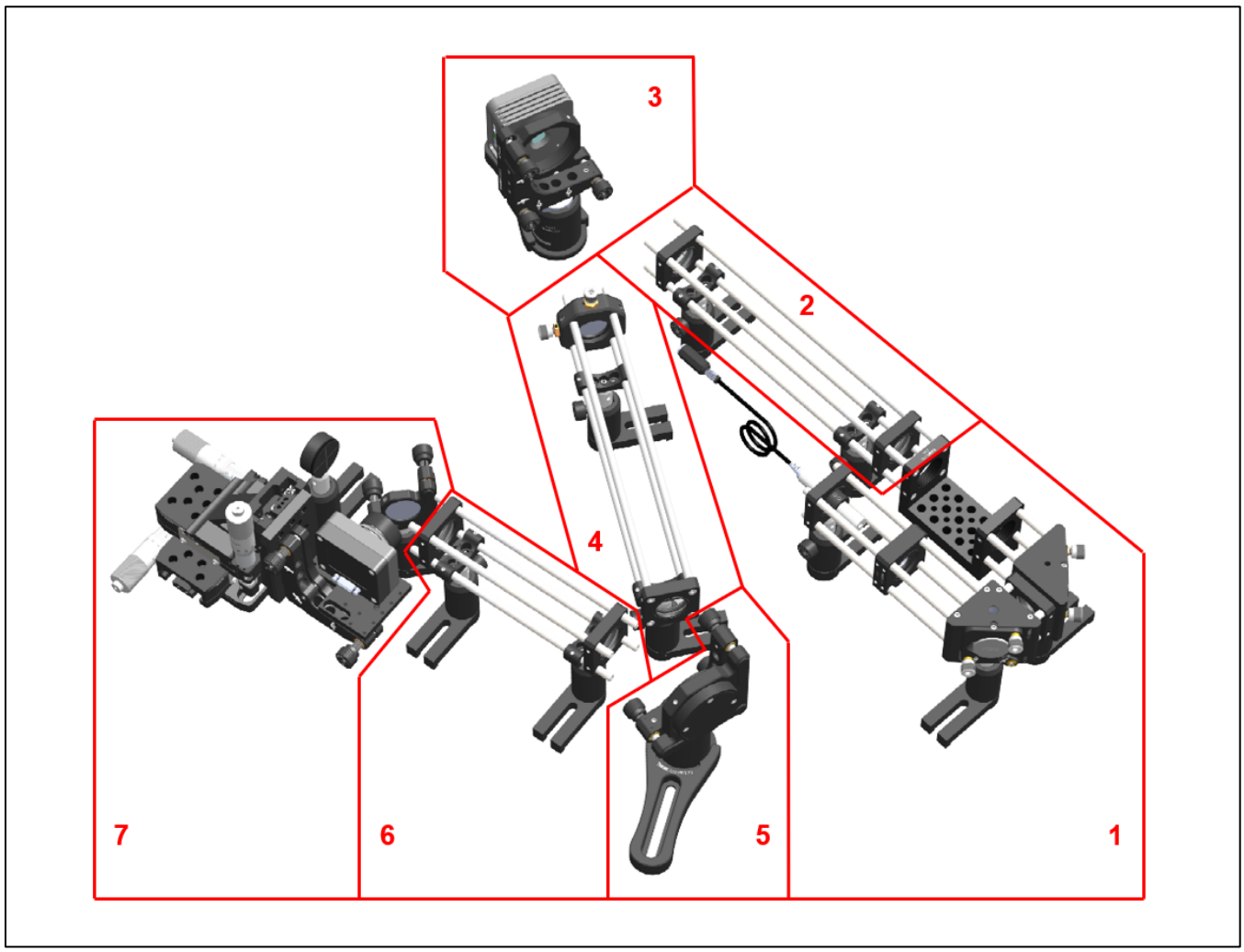


Figure 21 Woofer-Tweeter Two Deformable Mirror System Divided into Subassemblies

Subassembly	Qty.	AOKWT1(/M) Item #
1	1	635 nm Laser Diode Module, 0.30 mW
	1	LA1289-B
	1	LA1509-B
	2	PF10-03-P01
	1	AD11F
	1	AD1T
	1	CBB1(/M)
	1	CP33T
	1	KCB1(/M)
	1	KCB1C(/M)
	2	CP33(/M)
	3	TR2 (TR50/M)
	3	UPH2 (UPH50/M)
	4	ER1
	4	ER1.5
	4	ER6
2	1	LA1433-B
	1	LA1608-B
	2	CP33(/M)
	2	TR2 (TR50/M)
	2	UPH2 (UPH50/M)
	2	CP33B
	4	ER3
	4	ER8
3	1	DMH40-P01 (DMH40/M-P01)
	1	RS1.5P8 (RS38P4/M)
	1	KS2D
	1	RSH2(/M)
	1	PF125B
	1	SM2AB1
4	1	LA1134-B
	1	LA1708-B
	1	CXY1A
	1	CP33(/M)
	2	TR2 (TR50/M)
	2	UPH2 (UPH50/M)
	2	CP33B
	4	ER1
	4	ER10
5	1	DM140A-35-P01
	1	RS1.5P8 (RS38P4/M)
	1	KS2D
	1	RSH2(/M)

Subassembly	Qty.	AOKWT1(/M) Item #
5	1	PF125B
6	2	LA1608-B
	2	CP33(/M)
	2	TR2 (TR50/M)
	2	UPH2 (UPH50/M)
	2	CP33B
	4	ER05
	4	ER6
7	1	SM1A7
	1	LMR1(/M)
	1	BSN10
	1	KM100
	1	WFS20-5C(/M)
	1	KM200PM(/M)
	1	AE8E25ES (AE4M6MS)
	1	XRN-YZ(/M)
	1	XRN-B1(/M)
	3	XRN25P(/M)
	1	SM1A9
	1	CL5
	1	NE10A
	1	NE20A
	1	TR1.5 (TR40/M)
	2	TR2 (TR50/M)
	1	UPH1.5 (UPH40/M)
	2	UPH2 (UPH50/M)
Not Shown	3	CPA1
Not Shown	1	CPSA
Not Shown	1	DS5

Note: The above table is for the AOKWT1(/M) kit. For the packing list, see Chapter 11.1.

The basic assembly and alignment steps are similar for all the kits.

Step 1. Align subassemblies 1 and 2. A cage system alignment tool (CPA1) will aid in the alignment. Additionally, the CPSA and DS5 power supply should be connected to the laser diode module and powered ON.

Note: Proper laser safety handling procedures should be followed.

1) Secure three (3) TR posts to subassembly 1 and using three (3) post holders, secure the subassembly to the optical table, leaving enough room to position subassembly 2 and the DM / mount. Laying out the additional assemblies in the rough setup can aid in leaving room.

2) **Note:** The mirrors of subassembly 1 are pre-aligned such that the beam propagates coaxially with the center of the subassembly 2 cage system. If you are not certain the mirror alignment is correct follow steps a) through e) below, or else continue with sub-step 3.

   a) Temporarily attach subassembly 2 to the u-bench of subassembly 1, securing it with the setscrews in the CBB1(/M) u-bench.

   b) Using a CPA1 positioned just before the u-bench, adjust the angles of the mirror closest to the LD module such that the beam is centered on the CPA1.

   c) Move the CPA1 to the first lens of subassembly 2, then adjust the mirror further from the LD module until the beam spot is centered on the CPA1.

   d) Repeat steps 1-4 and 1-5 until the beam spot is centered on the CPA1 in both locations.

   e) Remove subassembly 2 from subassembly 1.

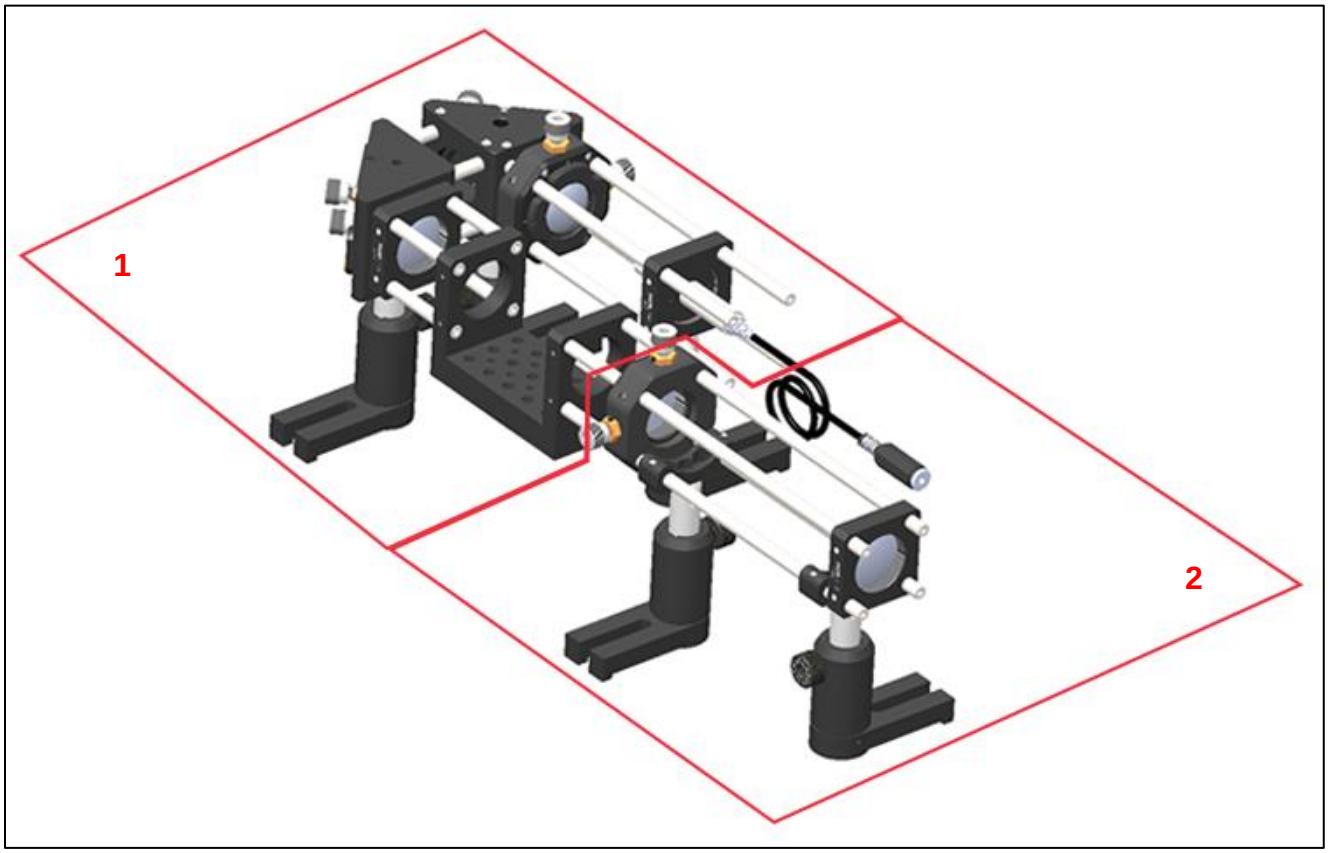


Figure 22 AOK5 First Two Preassembled Cage Subassemblies (Parts 1 and 2)

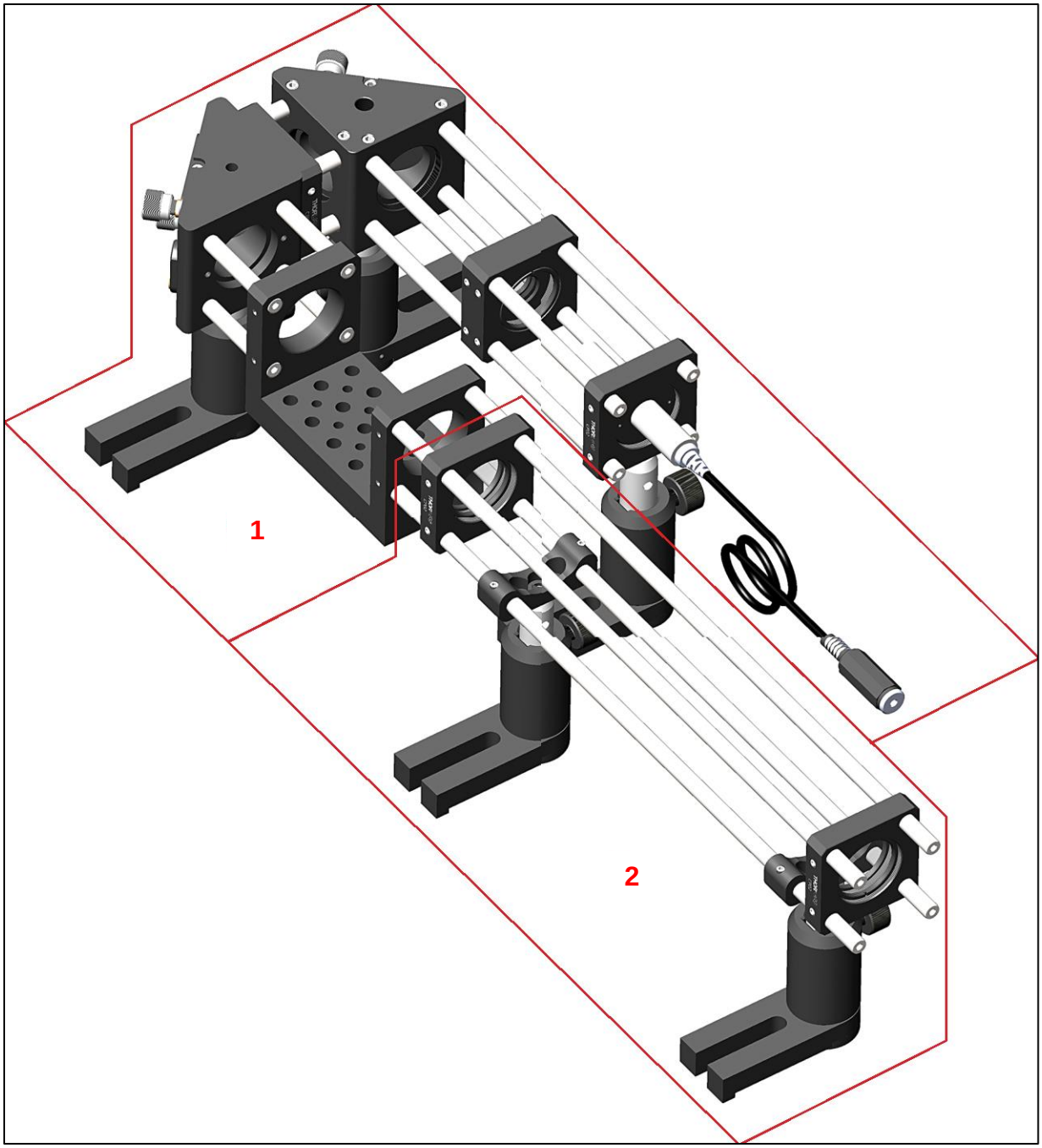


Figure 23 AOK8 or AOKWT1 First Two Preassembled Cage Subassemblies (Parts 1 and 2)

3) Adjust the heights of the three posts supporting section 1 such that the output beam is parallel to the optical table and at a height sufficient to be incident on the center of the DM, approximately 100 mm. Tighten the screws securing the post holders to the optical table, and secure the post holder thumb screws that secure the height of the subassemblies 1 and 2.

4) Attach subassembly 2 to the u-bench of subassembly 1 without tightening the u-bench set screws and adjust the subassembly 2 post holders to nominally support the subassembly parallel to the optical table.

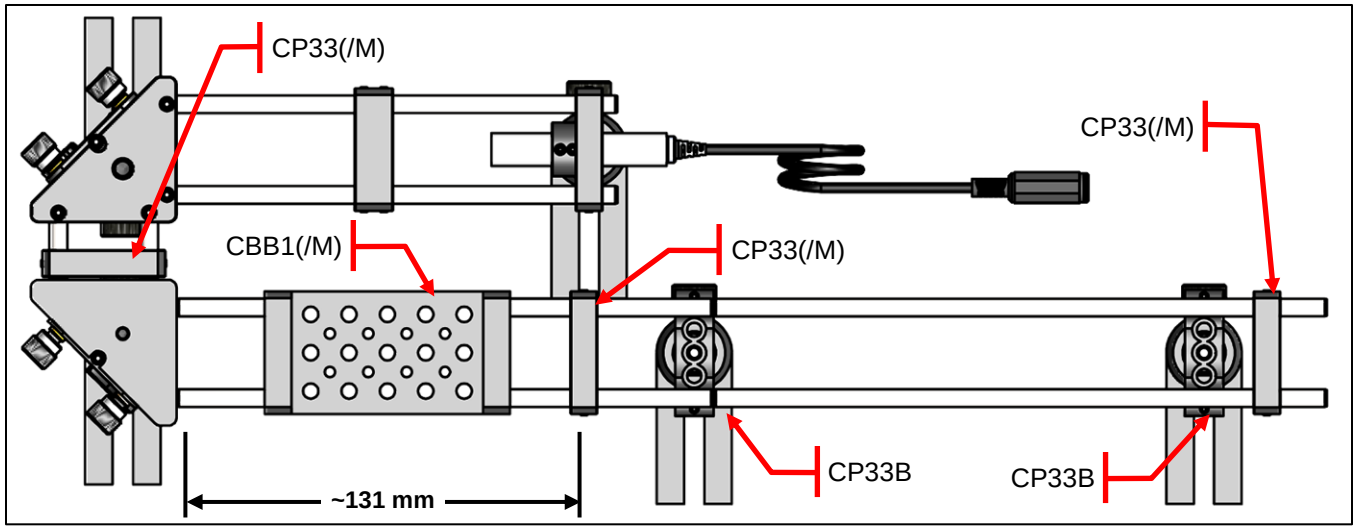


Figure 24 Achieving the Correct Optic Spacing with AOK8(L) kits

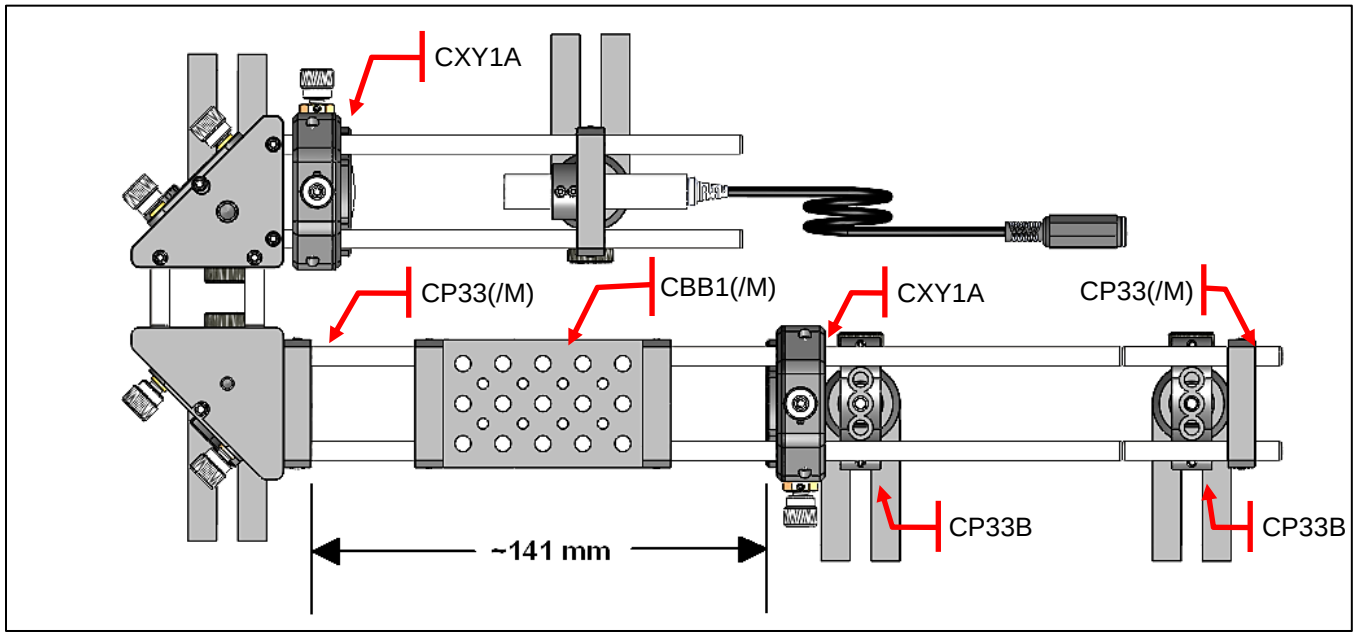


Figure 25 Achieving the Correct Optic Spacing with AOK5

5) With a CPA1 at the input side of the u-bench and one just before the subassembly 2 output lens, adjust the subassembly 2 post holders so that the beam spot is centered on the CPA1 near the subassembly 2 output lens. Then tighten the subassembly 2 post holders and secure the u-bench set screws. Do not overtighten the set screws.

6) Confirm the beam exiting subassembly 2 is parallel with the optical table. If not, re-check the beam passing through subassemblies 1 and 2 and make appropriate adjustments. **Piezoelectric Deformable Mirror Note:** The optical system of subassemblies 1 and 2 expand the beam from the laser diode module such that it overfills the DMH40/DMP40 mirror aperture. The beam diameter after subassembly 2 will be approximately 2 cm. **Note:** If the beam is not centered, use the XY adjustments on the CXY1A located after the CBB1(/M) to center the beam.

Step 2. Align the DM with the output beam.

1) Place a CPA1 in the beam path just before the CBB1(/M) u-bench.
2) Position the DM subassembly such that the DM mirror surface is spaced according to the kit and the type of mirror and lens relays being used. The DMH40/DMP40 spacing is shown in Figure 26 below. The DM140A spacing is shown in Figure 27 below. Note: if assembling an AOKWT Sample kit in the standard configuration, the DMH40/DMP40 is first.

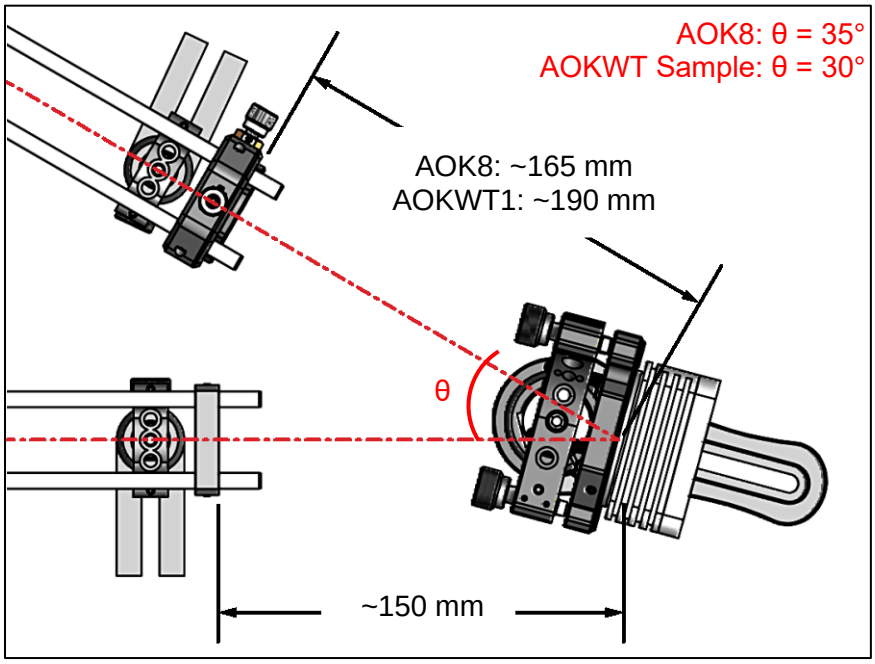


Figure 26 DMH40/DMP40 Deformable Mirror Alignment

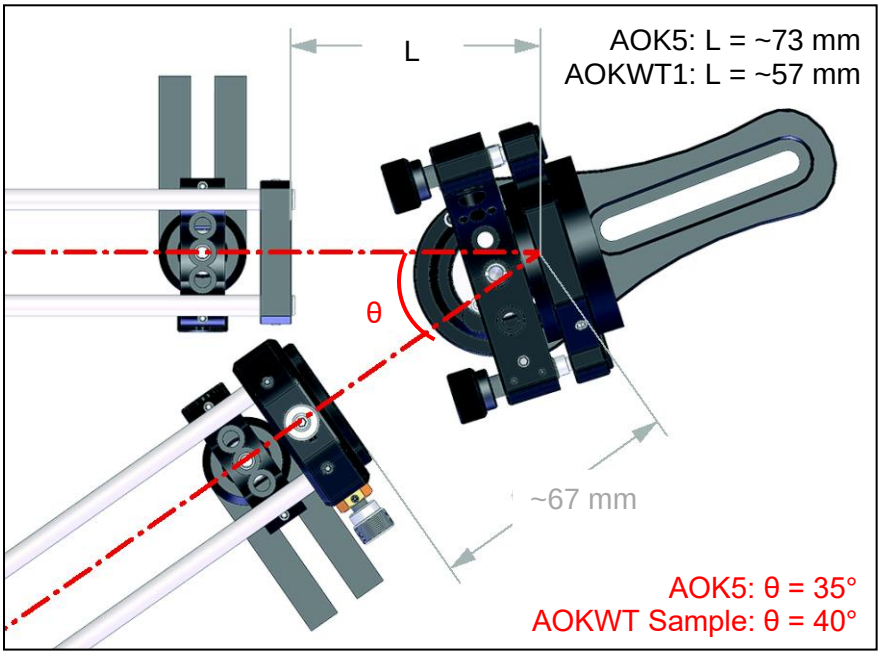


Figure 27 DM140A Deformable Mirror Alignment

3) Adjust the height of the DM such that beam spot is vertically centered on the DM.

4) Adjust the position of the DM such that the beam spot is centered on the DM mirror, and such that the reflected beam passes about 5.5 cm away from the laser diode module mount. This will leave enough room for positioning subassembly 4. Then tighten the screws securing the DM position and height.

5) Adjust the kinematic mount supporting the DM so that the reflected beam is parallel to the optical table.

Step 3. Align subassembly 4 with the reflected beam from the DM. If assembling a single DM AO Kit, skip Steps 4 and 5 and continue to Step 6.

1) With a CPA1 at the input side of subassembly 4, adjust the height of subassembly 4 such that the beam spot is centered vertically on the CPA1.

2) Place another CPA1 just before the output lens of subassembly 4 and adjust the position of subassembly 4 such that the beam is centered on the CPA1 at the input, and the small beam transmitted through the center of the CPA1 is nominally aligned with the output CPA1.

3) Secure the post holder at the input side of the subassembly such that it does not move on the table and have the thumb screw set so that the output side of the subassembly can be adjusted without the subassembly moving vertically.

4) Adjust the position of the output side post holder to center the beam spot horizontally on the CPA1 and secure the post holder to the optical table.

5) Adjust to the height of the output side of subassembly 4 such that the beam spot is centered on the CPA1 and secure the post holder thumb screw.

Step 4. **AOKWT Kits ONLY** - Align the center of the first DM to the center of the second DM.

1) Place a CPA1 in the beam path just before the CXY1A of the AOKWT subassembly 4.

2) Position the second DM subassembly such that the DM mirror surface is spaced according to the type of mirror and lens relays being used, commonly DM140A. The DM140A spacing is shown in Figure 27.

3) Subassembly 4 of the AOKWT1 is a 4-f beam reducer with a magnification ratio of approximately 0.30, resulting in the full 17 mm optical aperture and 14 mm pupil of the DMH40 being reduced to approximately 5.1 mm and approximately 4.2 mm, respectively, at the WFS lenslet array (for the woofer-tweeter AO Kits including the DMP40 the subassembly 4 is a 4-f beam reducer with a magnification ratio of approximately 0.42, resulting in the full 11.5 mm optical aperture and 10 mm pupil of the DMP40 being reduced to approximately 4.9 mm and approximately 4.3 mm, respectively, at the WFS lenslet array.)

Step 5. **AOKWT Kits ONLY** - Align subassembly 6 with the reflected beam from the DM.

1) With a CPA1 at the input side of subassembly 6, adjust the height of subassembly 6 such that the beam spot is centered vertically on the CPA1.

2) Place another CPA1 just before the output lens of subassembly 6 and adjust the position of subassembly 6 such that the beam is centered on the CPA1 at the input, and the small beam transmitted through the center of the CPA1 is nominally aligned with the output CPA1.

3) Secure the post holder at the input side of the subassembly such that it does not move on the table and have the thumb screw set so that the output side of the subassembly can be adjusted without the subassembly moving vertically.

4) Adjust the position of the output side post holder to center the beam spot horizontally on the CPA1 and secure the post holder to the optical table.

5) Adjust to the height of the output side of subassembly 6 such that the beam spot is centered on the CPA1 and secure the post holder thumb screw.

Step 6. Align the center of the DM to the center of the SH sensor.

1) The position of the beam splitter (BS) and SH sensor are determined by the proceeding lens relay. The EFL of the output lens of subassembly is 60 mm for the AOK8 and 75 mm for the AOK5 and AOKWT kits. Therefore, the mounts of the subassembly 4 output lens, the beamsplitter and WFS will be positioned very close together. Exercise caution when positioning the pellicle and WFS; the pellicle membrane is very fragile. The distance from the output surface of the output lens in the final lens relay to the BS plus the distance from the BS to the lenslet array of the WFS should be ~60 mm for the AOK8 and ~75 mm for the AOK5 and AOKWT kits.
2) Place the beam dump (LMR1(/M) assembly) in front of the transmitted beam. All the pieces should be at a height of ~100 mm from the optical bench to match the cage system and deformable mirror height.

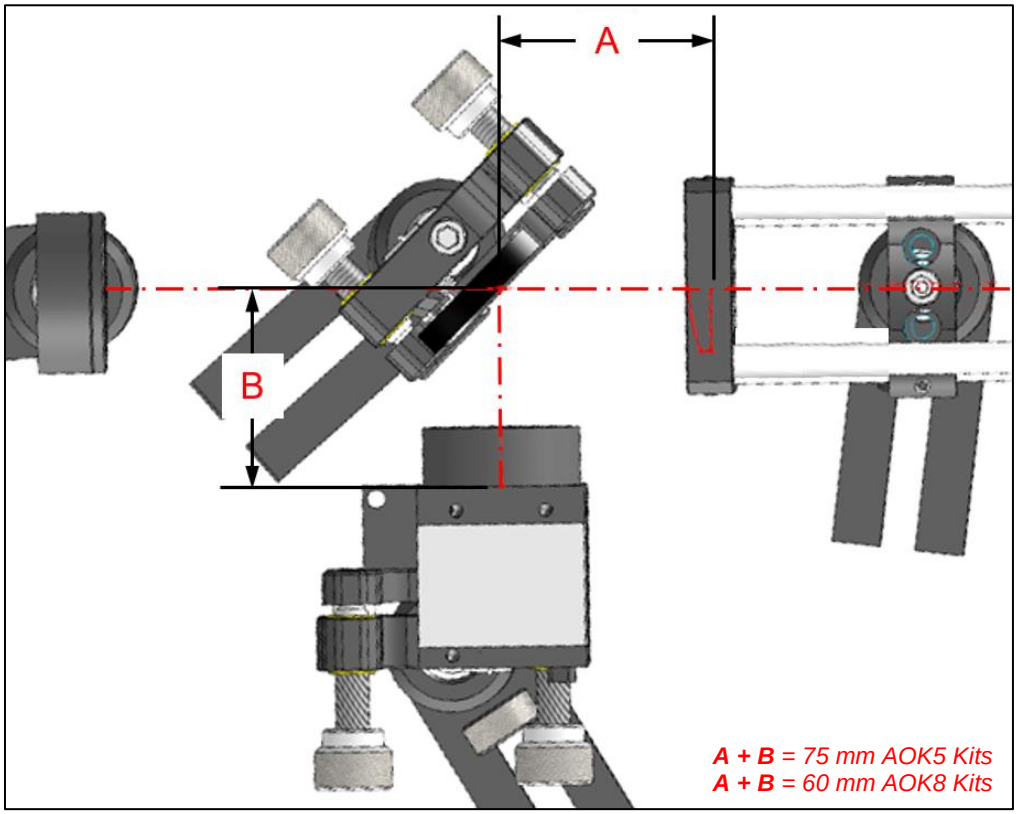


Figure 28 AO Kit with WFS40 shown Kit Alignment of the Beam Splitter, Alignment Plate, and Shack-Hartmann Sensor

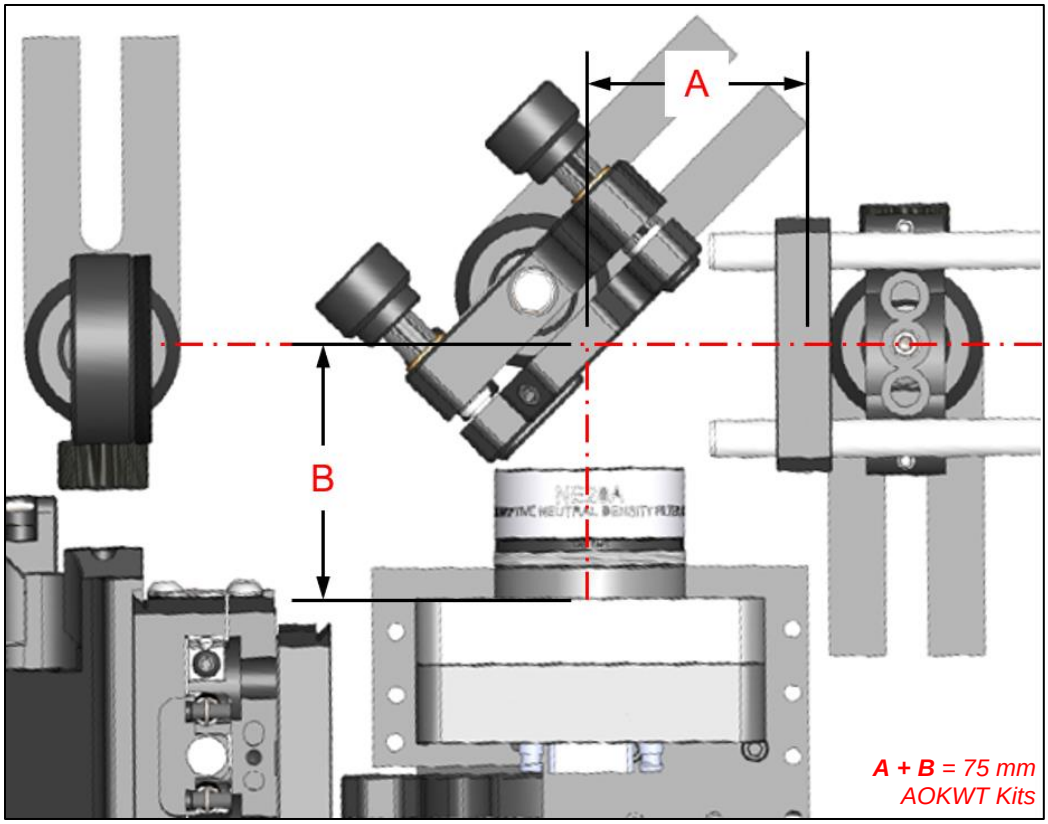


Figure 29 AOKWT Kit Alignment of the Beam Splitter, Alignment Plate, and Shack-Hartmann Sensor

3) With the WFS and DM connected to the computer, start the AO Kit application, and make sure the Shack-Hartmann window is showing.

4) Subassembly 4 of the AOK8 is a 4-f beam reducer with a magnification ratio of approximately 0.34, resulting in the full 17 mm optical aperture and 14 mm pupil of the DMH40 being reduced to approximately 5.7 mm and approximately 4.7 mm, respectively, at the WFS lenslet array (for single DM AO Kits including the DMP40 the subassembly 4 is a 4-f beam reducer with a magnification ratio of approximately 0.34, resulting in the full 11.5 mm optical aperture and 10 mm pupil of the DMP40 being reduced to approximately 3.9 mm and approximately 3.4 mm, respectively, at the WFS lenslet array.) The final lens relay subassembly of the AOK5 and AOKWT are 4-f relays projecting the image plane from the Multi DM to approximately 4.4 mm at the WFS lenslet array.

5) The fine tuning of the alignment is covered in Section 9.1.

Chapter 5 AO Control Software Architecture

5.1. Introduction

After years of selling AO Kits, Thorlabs realized a need for control software flexible enough to allow a user to run components independently, yet simultaneously, while also allowing the user easy access to running preconfigured AO systems. The AO control application has been developed based on software plugin modules to allow a user to add functionality to their application without needing to install a new application each time. Figure 30, below, graphically details the software plugin module interface concept.

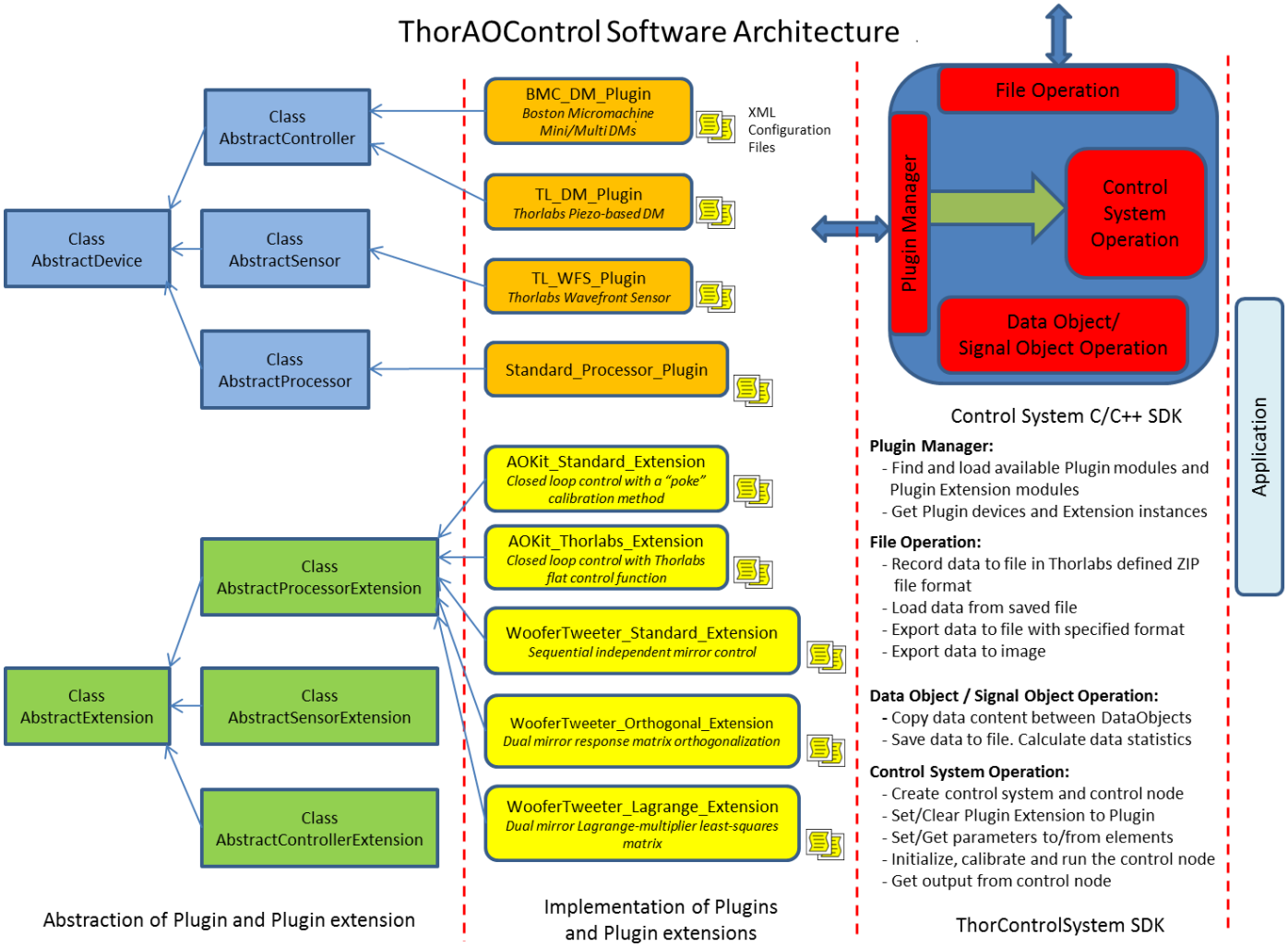


Figure 30 Software Description Diagram

5.2. Plugin Module

A plugin module is a dynamic link library (.dll) to support particular devices (sensors, controllers) or a control procedure (processor). The development of the plugin module must follow the pre-defined interfaces and protocols, to allow the Thorlabs AO Control Application software to identify and load the plugin modules. The third-party users can also develop their own plugin modules by following the same interfaces and protocols and add new devices or algorithms to the Thorlabs AO Control system without risk of destabilizing the core functionality.

There are three types of plugin modules: sensor plugin modules, controller plugin modules and processor plugin modules.

5.2.1. Sensor Plugin Modules

These modules are essentially wrapper DLLs and include functions to find, manage and control sensor devices. By default, the Thorlabs AO Control systems are delivered with the Thorlabs Wavefront Sensor Plugin Module (TL_WFS_Plugin.dll). This plugin works with all Thorlabs wavefront sensors.

5.2.2. Controller Plugin Modules

These modules are essentially wrapper DLLs and include functions to find, manage and control controller devices. By default, the Thorlabs AO control systems are delivered with either the Thorlabs Piezo-Based Deformable Mirror Plugin Module (TL_DM_Plugin.dll) or the BMC Mini/Multi Deformable Mirror Plugin Module (BMC_DM_Plugin.dll), depending on the mirror included in the Thorlabs AO Control system. The Thorlabs Piezo-Based Deformable Mirror Plugin Module works with all Thorlabs DMH40/DMP40 deformable mirrors, and the BMC Mini/Multi Deformable Mirror Plugin Module works with all Boston Micromachines' Mini- and Multi-Deformable Mirrors.

5.2.3. Processor Plugin Module

Processor plugin module is a software DLL that includes functions to initialize, calibrate and execute the open/closed loop control of the Thorlabs AO Control system. By default, the Thorlabs AO Control systems are delivered with a Standard Processor Plugin Module (Standard_Processor_Plugin.dll).

Software plugin modules for other manufacturer's DMs and wavefront sensors may be created. Please contact Thorlabs Technical Support at techsupport@thorlabs.com for more information.

5.3. Extension Module

Extensions are the software modules (.DLL) to expand the key functionalities of the base plugin modules, either sensor modules, controller modules or processor modules. Like plugin modules, there are pre-defined protocols and interfaces for the development of extension modules. The third-party users can follow these interfaces and protocols to develop their own extension modules to add extra functionality to the base plugin modules.

The factory-delivered sensor modules (TL_WFS_Plugin.dll) and controller modules (TL_DM_Plugin.dll, BMC_DM_Plugin.dll) already provide the full control of the devices and suit the needs in most AO applications. Sensor extensions and controller extensions could add little extra functionality to what are in the base modules but are not needed in most applications; the processor extensions, on the contrary, play an essential part in expanding the functionality of the processor modules. Because the factory-delivered processor module (Standard_Processor_Plugin.dll) works as a shell, it doesn't provide the concrete implementations of its functionalities such as initialization, calibration, and loop control. The processor module must load a processor extension to achieve those functionalities. Depending on the processor extensions, the same functionality may have different implementations. For example, the AO Kit DMP40 Processor Extension calibrates the system by measuring the properties of the optical setup between the Deformable Mirror and the Wavefront Sensor, while the AO Kit Standard Processor Extension calibrates the system with "Poke" method.

No sensor extensions and controller extensions are delivered with the Thorlabs AO Control software. Thorlabs provides five processor extensions, each implements a different type of AO control:

5.3.1. AO Kit DMP40 Processor Extension Module

This module (AOKit_DMP40_Extension.dll) is implemented in our AOK7, AOK8, and AOK9 AO Kits to control one Thorlabs DMH40 or DMP40 DM and one Thorlabs WFS. It only works for systems based exclusively on Thorlabs devices. The calibration and loop control of the DM/WFS are done using unique DMP40 DLL function calls. Within the control loop, the calculated Zernike coefficients for the measured wavefront are read from the WFS. These values are input to a DMP40 DLL function to calculate the new DM segment voltages to compensate for the wavefront deviations from flat. The DM segment voltages are then input to a DMP40 DLL function to update the DMH40/DMP40 segment voltages.

5.3.2. AO Kit Standard Processor Extension Module

This module (AOKit_Standard_Extension.dll) is implemented in our AOK1 and AOK5 AO Kits, to control one deformable mirror and one wavefront sensor. In addition to the zonal poke-calibration method, this module also includes a modal (Zernike) poke-calibration method. This process allows one to set min/max values for control signals during the calibration process, as well as a closed loop control correction factor.

During the **zonal poke algorithm**, with all the actuators set at an offset voltage (% of full scale) the measured wavefront is set as the reference wavefront. As each actuator is set to a user defined maximum value (% of full scale) the measured Shack-Hartmann spot deviations are measured relative to reference Shack-Hartmann spot locations. The data for all poked actuators is used to create an influence matrix. The pseudo-inverse of the influence matrix is used to calculate the system correction matrix.

During the **modal poke algorithm**, with all the actuators set at an offset voltage (for the DMH40/DMP40, this is typically 100 V / 150 V, respectively) the measured wavefront is set as the reference wavefront. Near-Zernike modes are put on the deformable mirror rather than poking individual mirror actuators. For each Zernike mode, the Shack-Hartmann spot deviations are calculated as the difference between the measured spot locations with a positive Zernike coefficient and a negative Zernike coefficient set to the mirror. The data for all Zernike pokes is used to create an influence matrix. The pseudo-inverse of the influence matrix is used to calculate the system correction matrix.

During AO control, the system correction matrix is multiplied by the measured Shack-Hartmann spot deviations to calculate the correction signal to be applied to the deformable mirror. In the case of a DMH40 or DMP40 mirror, the correction signals are Zernike coefficients; while for BMC mirrors, the correction signals are actuator voltages.

5.3.3. AO Kit Woofer-Tweeter Lagrange-based Processor Extension Module

This module (AOKit_WooferTweeter_LagrangeBased_Extension.dll) is based on the following two papers:

- Weiyao Zou, et. al.; 1 July 2011 / Vol. 2, No. 7 / BIOMEDICAL OPTICS EXPRESS, 1986
- Weiyao Zou, et. al.; 15 Nov. 2008 / Vol. 33, No. 22 / OPTICS LETTERS, 2602

During the calibration process, the influence matrix for each mirror is measured. A Thorlabs DMH40/DMP40 deformable mirror will be calibrated using a modal poke algorithm. A BMC Multi-deformable mirror will be calibrated using a zonal poke algorithm. The zonal versus modal poke is explained above in section **AO Kit Standard Processor Extension Module**.

Equation 1, the control matrix equation, is from the referenced publication. The Lagrange multiplier is a weighting factor between the two deformable mirrors, to balance the influence of the mirrors. In the limit of the Lagrange multiplier equal to zero, the equation reduces to woofer control alone. A and B are determined during the calibration process.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} A^T A + \lambda_1 I_1 & \beta A^T B \\ \beta B^T A & \beta^2 B^T B + \lambda_2 I_2 \end{bmatrix}^{-1} \begin{bmatrix} A^T \\ \beta B^T \end{bmatrix} S \; ; \qquad \text{(Eq. 1)}$$

- A ≡ woofer influence matrix [n_{SH} x n_w], n_w = # woofer control signals & n_{SH} = # SH spot deviations
- B ≡ tweeter influence matrix [n_{SH} x n_t], n_t = # tweeter control signals & n_{SH} = # SH spot deviations
- I_1 ≡ identity matrix [n_w x n_w]
- λ_1 ≡ damping factor for the woofer (Starting value = median eigenvalue of $A^T A$)
- I_2 ≡ identity matrix [n_t x n_t]
- λ_2 ≡ damping factor for the tweeter (Starting value = median eigenvalue of $B^T B$)
- β ≡ Lagrange multiplier
- S ≡ SH spot deviation vector [n_{SH} x 1]

- X ≡ woofer control signals [n_w x 1]
- Y ≡ tweeter control signals [n_t x 1]

A modification from the published method was made to the equation: an added 2nd Lagrange-multiplier allows isolation of either the woofer or tweeter control matrix.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = g \begin{bmatrix} \xi A^T A + \lambda_1 I_1 & \xi\beta A^T B \\ \xi\beta B^T A & \beta^2 B^T B + \lambda_2 I_2 \end{bmatrix}^{-1} \begin{bmatrix} \xi A^T \\ \beta B^T \end{bmatrix} S \; ; \qquad \text{(Eq. 2)}$$

- A ≡ woofer influence matrix [n_{SH} x n_w], n_w = # woofer control signals & n_{SH} = # SH spot deviations
- B ≡ tweeter influence matrix [n_{SH} x n_t], n_t = # tweeter control signals & n_{SH} = # SH spot deviations
- I_1 ≡ identity matrix [n_w x n_w]
- λ_1 ≡ damping factor for the woofer (Starting value = median eigenvalue of $A^T A$)
- I_2 ≡ identity matrix [n_t x n_t]
- λ_2 ≡ damping factor for the tweeter (Starting value = median eigenvalue of $B^T B$)
- β ≡ Lagrange multiplier (original)
- ξ ≡ Lagrange multiplier (added)
- S ≡ SH spot deviation vector [n_{SH} x 1]
- g ≡ closed loop control scale factor (added)
- X ≡ woofer control signals [n_w x 1]
- Y ≡ tweeter control signals [n_t x 1]

After each influence matrix is calculated, a singular value decomposition (SVD) on each of the influence matrices is performed and yields the singular values for each mirror. That is, for matrix $\boldsymbol{A}$, it may be decomposed such that $\boldsymbol{A = UWV^T}$, where ***'T'*** indicates a matrix transpose, $\boldsymbol{U}$ is a a matrix whose columns are eigenvectors of $\boldsymbol{AA^T}$, $\boldsymbol{W}$ is a diagonal matrix with singular values along its diagonal, and $\boldsymbol{V}$ is a matrix whose columns are eigenvectors of $\boldsymbol{A^T A}$. The same is true for matrix $\boldsymbol{B}$.

The user may select a band of mirror eigenmodes to use during closed-loop control by adjusting lower and upper threshold values for each mirror. The singular values below the lower threshold and above the upper threshold are set to zeros. Then, using the modified singular values the modified influence matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are recalculated, and subsequently the new system control matrix is calculated using the new influence matrix. The eigenmodes associated with each singular value are subsequently 'disabled' in the system control.

5.3.4. AO Kit Woofer-Tweeter Orthogonal-based Processor Extension Module

This module (AOKit_WooferTweeter_OrthogonalBased_Extension.dll) is based on the following paper:

- Chaohong Li, et. al.; 2 Aug 2010 / Vol. 18, No. 16 / OPTICS EXPRESS

During the calibration process, the influence matrix for each mirror is measured. A Thorlabs DMH40/DMP40 deformable mirror will be calibrated using a modal poke algorithm. A BMC Multi-deformable mirror will be calibrated using a zonal? poke algorithm. The zonal versus modal poke is explained above in section **AO Kit Standard Processor Extension Module**.

In a woofer-tweeter control system, an important aspect is how one prevents the two mirrors from "battling" each other to correct for wavefront aberrations simultaneously. In this method, the coupling between the two mirror response matrices is minimized by modifying the measured tweeter influence matrix such that the resulting matrix is orthogonal to the woofer influence matrix. Eq. 3 shows the influence / response equation for the system, where $\boldsymbol{D}$ is the mirror influence/response matrix that characterizes the systems response, the measured spot deviations $\boldsymbol{S}$ caused by a setting actuator commands $\boldsymbol{C}$.

$$S = DC; \qquad \text{(Eq. 3)}$$

The goal is to create a new matrix, $\boldsymbol{D_t'}$ that is orthogonal to $\boldsymbol{D_w}$. To do so, $\boldsymbol{D_t' = D_t - D_{tw}}$, where $\boldsymbol{D_{tw}}$ is the projection of $\boldsymbol{D_t}$ onto $\boldsymbol{D_w}$. The resulting equation for the orthogonal matrix is $\boldsymbol{D_t' = D_t - D_w(D_w^+ D_t)}$, where the '+' indicates the pseudo-inverse. Eq. 4 shows the resulting response equation, where $\boldsymbol{S}$ is the vector of WFS spot deviations, $\boldsymbol{D_{wt}}$ is the combined woofer and orthogonal tweeter influence matrix, $\boldsymbol{D_w}$ is the woofer influence matrix, $\boldsymbol{D_t'}$ is the tweeter influence matrix orthogonal to the woofer influence matrix, $\boldsymbol{Z_w}$ is the vector of Zernike coefficients used to control the DMH40/DMP40 deformable mirror, and $\boldsymbol{V_t}$ is the vector of control voltages for the BMC deformable mirror.

$$S = D_{wt}C_{wt} = [D_w \quad D_t'] \begin{bmatrix} Z_w \\ V_t \end{bmatrix} \qquad \text{(Eq. 4)}$$

From this equation the control system equation is calculated (Eq. 5), where $\boldsymbol{D_{wt}^+}$ is the control matrix, and '+' indicates the pseudo inverse.

This equation is a deviation from the approach detailed in the referenced paper. In the paper, the combined influence matrix also includes sub-matrices for removing piston, tip and tilt from the system. This is not implemented since we control our DMH40/DMP40 deformable mirror by relative Zernike coefficients, piston, tip and tilt are not included. To remove these from the BMC deformable mirror the deformable mirror eigenmodes are suppressed.

$$D_{wt}^+ S = C_{wt} \qquad \text{(Eq. 5)}$$

For each deformable mirror influence matrix, the singular values are calculated. The singular values are calculated using a singular value decomposition (SVD) method. That is, for matrix $\boldsymbol{A}$, it may be decomposed such that $\boldsymbol{A = UWV^T}$, where $\boldsymbol{'T'}$ indicates a matrix transpose, $\boldsymbol{U}$ is a a matrix whose columns are eigenvectors of $\boldsymbol{AA^T}$, $\boldsymbol{W}$ is a diagonal matrix with singular values along its diagonal, and $\boldsymbol{V}$ is a matrix whose columns are eigenvectors of $\boldsymbol{A^T A}$.The user may select a band of mirror eigenmodes to use during closed-loop control by adjusting lower and upper threshold values for each mirror. The singular values below the lower threshold and above the upper threshold are set to zeros. Then, using the modified singular values the modified influence matrices $\boldsymbol{D_w}$ and $\boldsymbol{D_t'}$ are recalculated, and subsequently the new system control matrix is calculated using the new influence matrix. The eigenmodes associated with each singular value are subsequently 'disabled' in the system control matrix, $\boldsymbol{D_{wt}^+}$.

5.3.5. AO Kit Woofer-Tweeter Standard Processor Extension Module

This module (AOKit_WooferTweeter_Standard_Extension.dll) is designed to work with two deformable mirrors and one wavefront sensor. In a typical woofer tweeter system, the woofer deformable mirror would have fewer actuators with larger stroke compared with the tweeter deformable mirror. This is the case when using a Thorlabs DMH40/DMP40 deformable mirror as a woofer and the BMC Multi deformable mirror as a tweeter. Although this is the preferred configuration, and one that will yield better results, this extension module will allow a user to use either deformable mirror as the woofer and or tweeter.

During calibration, a Thorlabs DMH40/DMP40 deformable mirror will be calibrated using a modal poke algorithm. A BMC Multi or Mini deformable mirror will be calibrated using a zonal/modal? poke algorithm. The zonal versus modal poke is explained above in section **AO Kit Standard Processor Extension Module**.

During AO control, a wavefront sensor measurement is taken and the woofer system correction matrix is multiplied by the measured Shack-Hartmann spot deviations to calculate the correction signal to be applied to the woofer deformable mirror. After the correction signals are applied to the woofer, a new wavefront sensor measurement is taken and the tweeter system correction matrix is multiplied by the measured Shack-Hartmann spot deviations to calculate the correction signal to be applied to the tweeter deformable mirror. The correction signal is applied to the tweeter, and the process starts again. In the case of a DMH40/DMP40 mirror, the correction signals are Zernike coefficients; while for BMC mirrors, the correction signals are actuator voltages.

For each deformable mirror influence matrix, the singular values are calculated. The user may select a band of mirror eigenmodes to use during closed-loop control by adjusting lower and upper threshold values for each mirror. The singular values below the lower threshold and above the upper threshold are set to zeros. Then, using the

modified singular values the modified influence matrices are recalculated. The eigenmodes associated with each singular value are subsequently ‘disabled’ in the system control.

5.4. ThorControl System SDK

Some users may wish to create their own AO applications. Therefore, in addition to a fully functional stand-alone application, we provide a low-level support library easily accessible by any modern software development environment. The remainder of this manual will detail the stand-alone software application, while the low-level support library is documented in the API manual: “Adaptive Optics Kit, Programmer’s API Guide.pdf”.

The stand-alone application (ThorControlApp.exe) was designed to provide users with a flexible GUI by which to setup and run various AO related devices and user defined AO systems.

Chapter 6 Operating Instruction - Main Window

After installing the Thorlabs AO Control software, as detailed in Section 4.1, a shortcut icon will be placed on the desktop (see icon at the right). Start the software by double-clicking this desktop icon or by using the Windows menu:



Start à Thorlabs ThorAOControl à ThorAOControlApp.exe

When the AO Control Application is initially run, no user profiles and systems will be available (see Figure 31). Please follow instructions in Sections 6.1.3, 7.2.1, 7.2.2 and 7.3 for information about creating user profiles and systems. After user profiles and systems are created, they will appear in the lower region of the main window (see Figure 32).

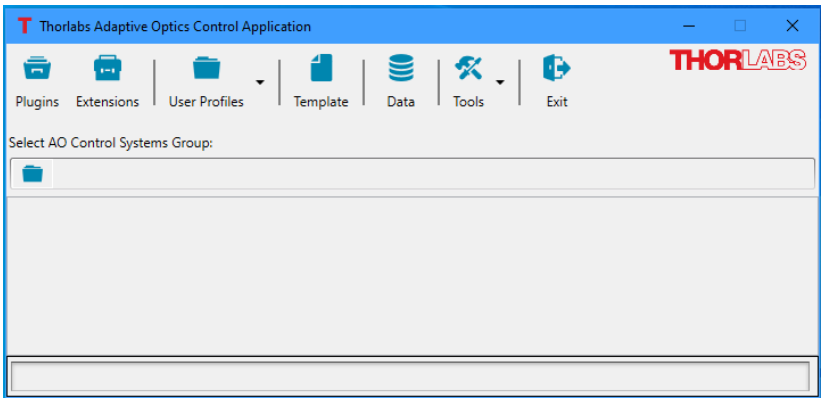


Figure 31 The Parent Window of the AO Control Software when Initially Run

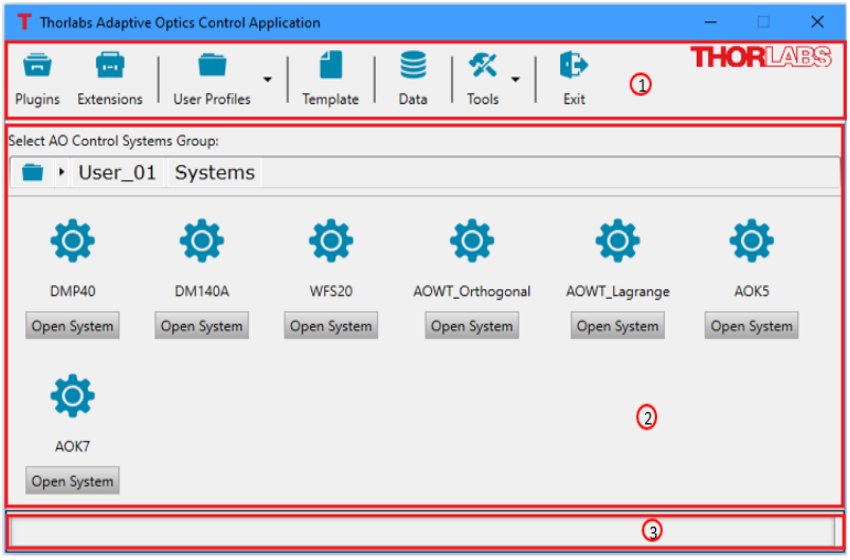


Figure 32 The Parent Window of the AO Control Software After Some Systems Setup

Main Window GUI Areas:

1. Toolbar
2. User profiles and control systems group
3. Status bar

6.1. Toolbar

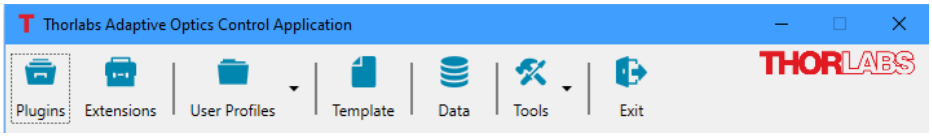


Figure 33 Main Window Toolbar

6.1.1. Plugins

When the Thorlabs AO Control Application is started, the application initialization searches for plugin DLLs in the default plugin installation directory:

C:\Program Files\Thorlabs\ThorAOControl\Plugins\[Plugin_Module_Folder]\Plugin_Module\Bin

After a plugin is loaded successfully, the application initializes this plugin with the default value from the configuration file which is located at:

C:\Users\[user_name]\AppData\Roaming\Thorlabs\ThorAOControl\\Plugins

The available plugins can be viewed by clicking the **Plugins** icon ( ) at the top left of the main window. A window titled Plugins will be displayed, showing the software plugin modules and information about the detected devices / procedures associated with each plugin module, see Figure 34. If the plugin for a device is not visible, please verify:

(1) The device driver is installed correctly,

(2) The USB cable between the device and the computer is securely connected, and that the power to the device is turned on, if applicable,

Once verified, click the icon ( ) in the upper right corner of the Plugins window to refresh the displayed plugins.

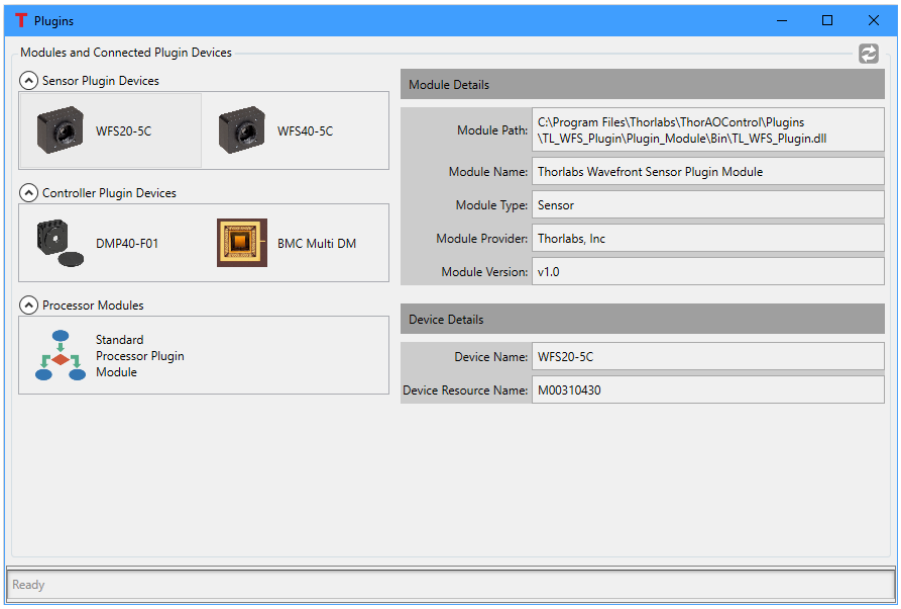


Figure 34 The Plugins Window shows that at least one device related to the displayed plugin was detected.

Figure 34 above shows there is one WFS20-5C connected that is associated with module named "Thorlabs Wavefront Sensor Plugin Module". Details about the module will be displayed in the right side of the window. The

details include the filename of the software module and the path to the folder in which the module is installed, the descriptive module name, the module type, module provider, module version, device name (item number) and the device resource name. For Thorlabs designed and manufactured items, the device resource name is the serial number.

6.1.2. Extensions

When the Thorlabs AO Control Application is started, the application initialization searches for extension DLLs in the default extension installation directory:

C:\Program Files\Thorlabs\ThorAOControl\Extensions\[Extension_Module_Folder]\Extension_Module\Bin

After an extension is loaded successfully, the application initializes this extension with the default value from the configuration file which is located at:

C:\Program Files\Thorlabs\ThorAOControl\Extensions\[Extension_Module_Folder]\Extension_Module\Config

The available extensions can be viewed by clicking the **Extensions** icon ( ). A window titled Extensions will be displayed, showing the software extension modules on the left and information about each extension module on the upper right panel, see Figure 35.

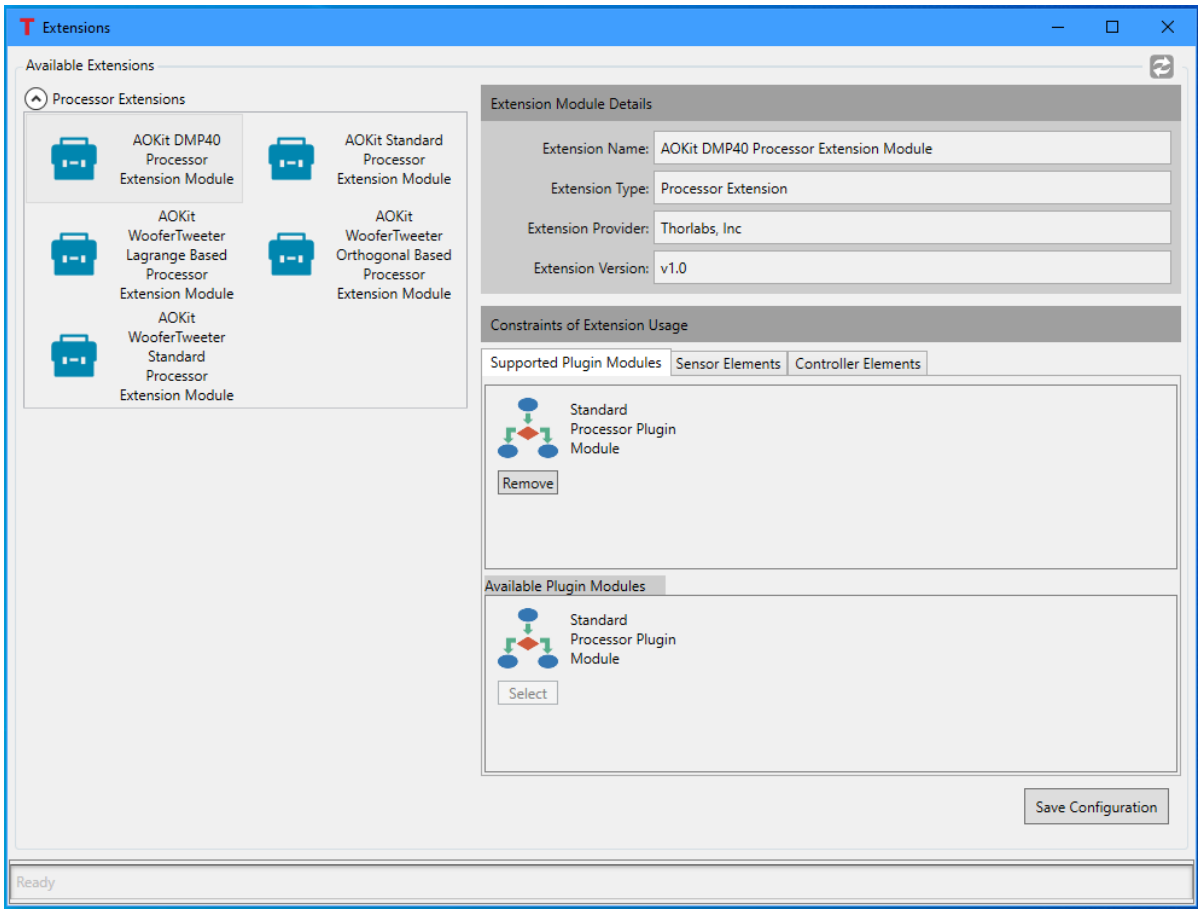


Figure 35 The Extensions Window shows the available plugin extensions.

Each extension module supports specific processor, sensor and controller plugins, as shown in the lower right panel titled **Constraints of Extension Usage** in Figure 36. An extension module must be configured before it can be used in the Thorlabs AO Control Application.

Supported Plugin Modules Tab

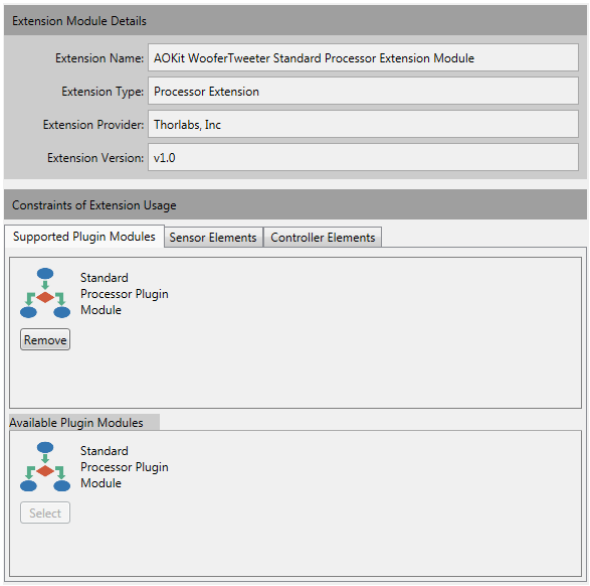


Figure 36 Supported Plugin Modules Tab for Processor Extension

This is used to select the base plugin module for the extension. Click **Select** button under a plugin icon from the list of **Available Plugin Modules** to add the selected plugin to the list of **Supported Plugin Modules**. Usually, the extension can only have one base plugin module.

All types of extensions must choose the base plugin module when configured. Besides that, the processor extension needs to select the base sensor plugin modules and base controller plugin modules for the sensor element and controller element used in the control methods it implements.

Sensor Elements Tab



Figure 37 Sensor Elements for Processor Extension

This tab page is only visible when configuring the processor extension and is used to select the base sensor plugins, which can serve as the sensor element in the implementation of the control methods. Click **Select** button under a sensor plugin icon from the list of **Available Sensor Plugin Modules** to add the selected sensor plugin to the list of **Supported Sensor Plugin Modules**.

- **Number of Sensors Employed in Algorithm** – This read-only value is returned by the processor extension and indicates the number of sensor elements needed in the control methods.

Figure 39, as an example, shows that AO Kit Woofer-Tweeter Standard Processor Extension Module needs one sensor element and can use Thorlabs Wavefront Sensor Plugin Module in the implementation.

Controller Elements Tab

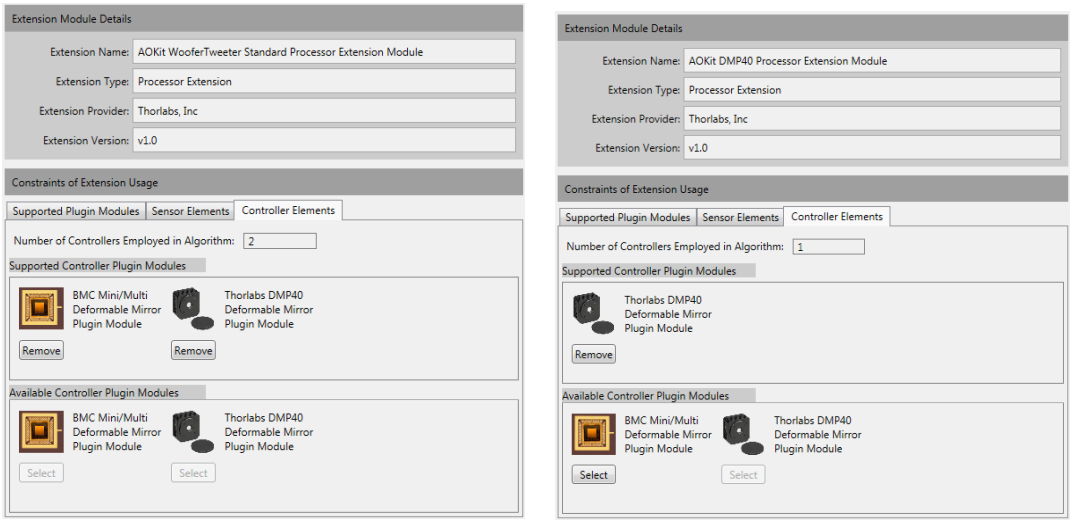


Figure 38 (a) Controller Elements for AO Kit Woofer-Tweeter Standard Processor Extension

(b) Controller Elements for AO Kit DMH40/DMP40 (DMP40 shown) Processor Extension

This tab page is only visible when configuring the processor extension and is used to select the controller plugins, which can serve as the controller elements in the implementation of the control methods. Click **Select** button under a controller plugin icon from the list of **Available Controller Plugin Modules** to add the selected controller plugin to the list of **Supported Controller Plugin Modules**.

- **Number of Controllers Employed in Algorithm** – This read-only value is returned by the processor extension and indicates the number of controller elements needed in the implementation.

Figure 38(a) shows that the AO Kit Woofer-Tweeter Standard Processor Extension Module needs two DMs in the implementation and can use both BMC Mini/Multi DMs and Thorlabs DMH40/DMP40 DMs. Figure 38(b) shows that AO Kit DMP40 Processor Extension uses one DM in the implementation and can only use Thorlabs DMP40/DMH40 DM.

Save Configuration – Click this button to save all the configurations to a file associated with each extension module. The configuration file can be found:

C:\Program Files\Thorlabs\ThorAOControl\Extensions\[Extension_Module_Folder]\Extension_Module\Config\ ExtensionApplicabilityConfig.xml

6.1.3. User Profiles

User Profiles allow multiple users to setup and group AO control systems, as well as define systems to independently operate sensors or controllers. Initially there are no user profiles setup. Clicking the User Profiles icon ( ) at the top of the main window displays the drop-down menu shown in Figure 39.

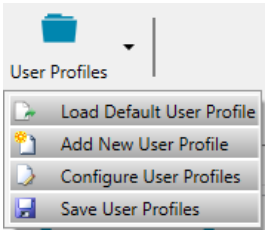


Figure 39 User Profiles Drop-Down Menu

6.1.3.1. Load Default User Profile

Click this button to load the default user profile. A default user profile has two control groups and each control group has default control systems, as shown in Figure 40 and Figure 41.

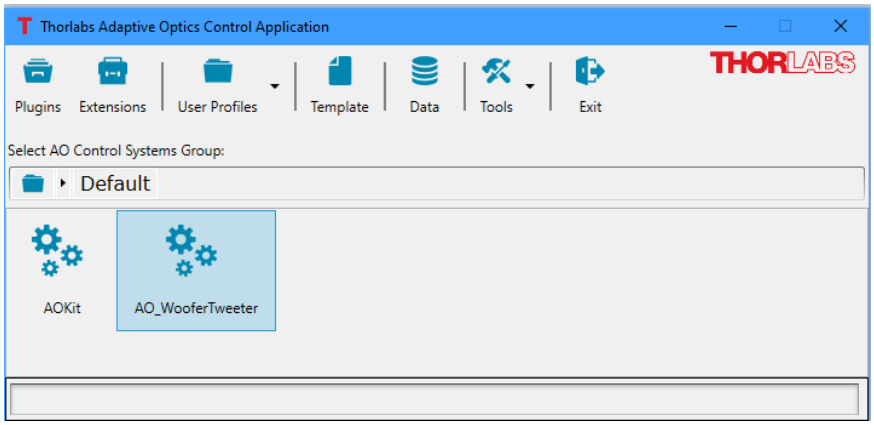
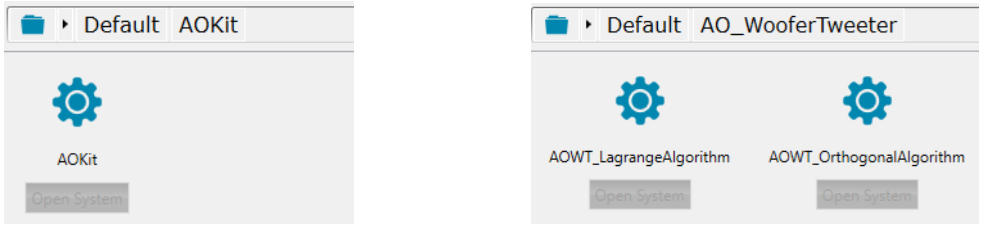


Figure 40 Default user profile has two control groups: AOKit and AO_WooferTweeter



(a) (b)

Figure 41 Default control systems in default user profile

Initially no devices are assigned to the default control systems. If user moves the cursor over the grayed-out **Open System** button, a message box will be popped up to remind user to configure the default user profile. See Figure 42. See Chapter 7 for instructions on configuring the user profile.

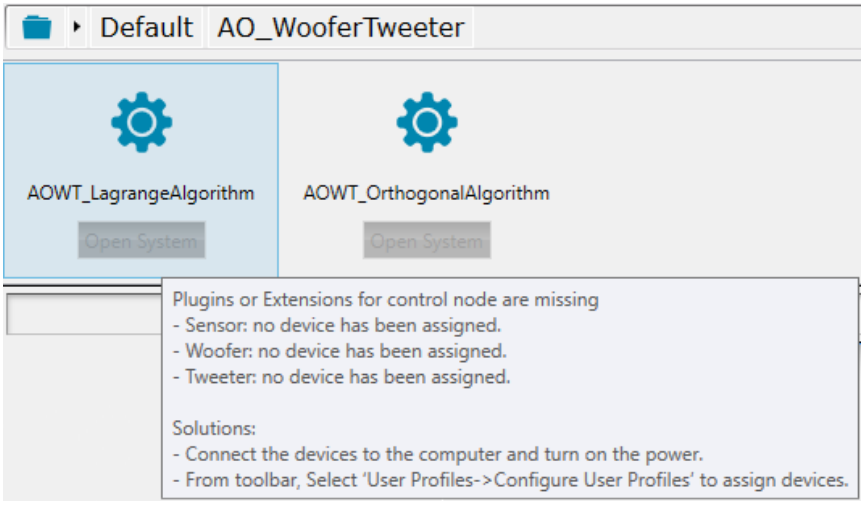


Figure 42 Popup window shows the control system status and reminds user to configure the user profile.

6.1.3.2. Add New User Profile

Click this button to set up a new user profile. The New User Profile Window will appear (Figure 43). Enter the username in the Profile Name field and click OK.

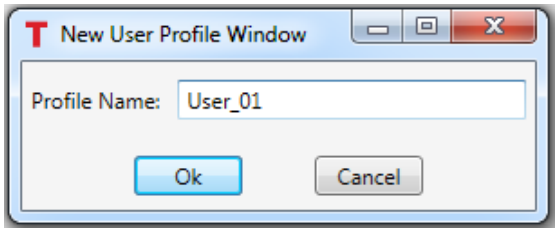


Figure 43 New User Profile Window. The Profile Name is the user name.

6.1.3.3. Configure User Profiles

Click this button to configure the user profiles. The User Profiles window will appear (Figure 44). Note, it is initially blank if neither the default user profile was loaded nor other user profiles were created.

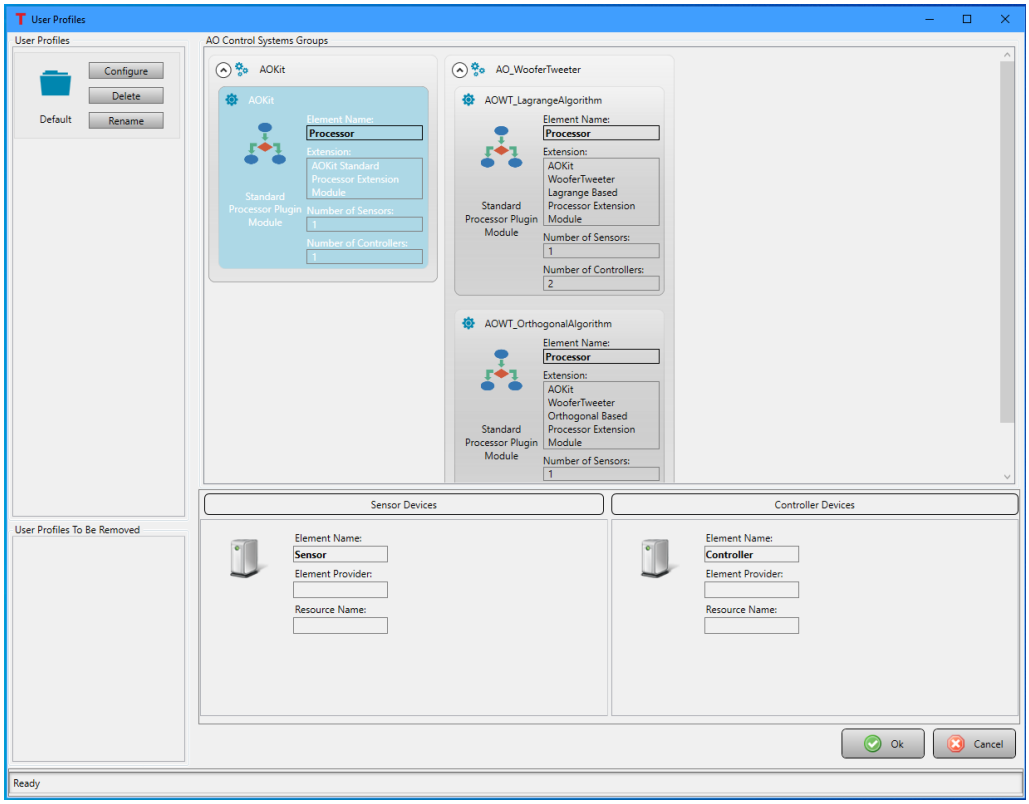


Figure 44 User Profile Window showing a newly loaded default user profile.

The top-right section of the **AO Control Systems Groups** shows the information of the control groups, the control systems and the Processors (if available). The bottom-right section shows the information of the sensor devices and / or controller devices used in the highlighted control system.

Click **Configure** button within the highlighted User Profile to add new Control Groups / Systems to the User Profile. Please see Chapter 7 for instructions on creating a Control Group / System.

Click the **Delete** button next to the highlighted User Profile to remove the selected User Profile from **User Profiles** pane. The User Profile will be temporarily moved to **User Profiles To Be Removed** pane, see Figure 45.

Click the **Rename** button to change the selected user profile name.

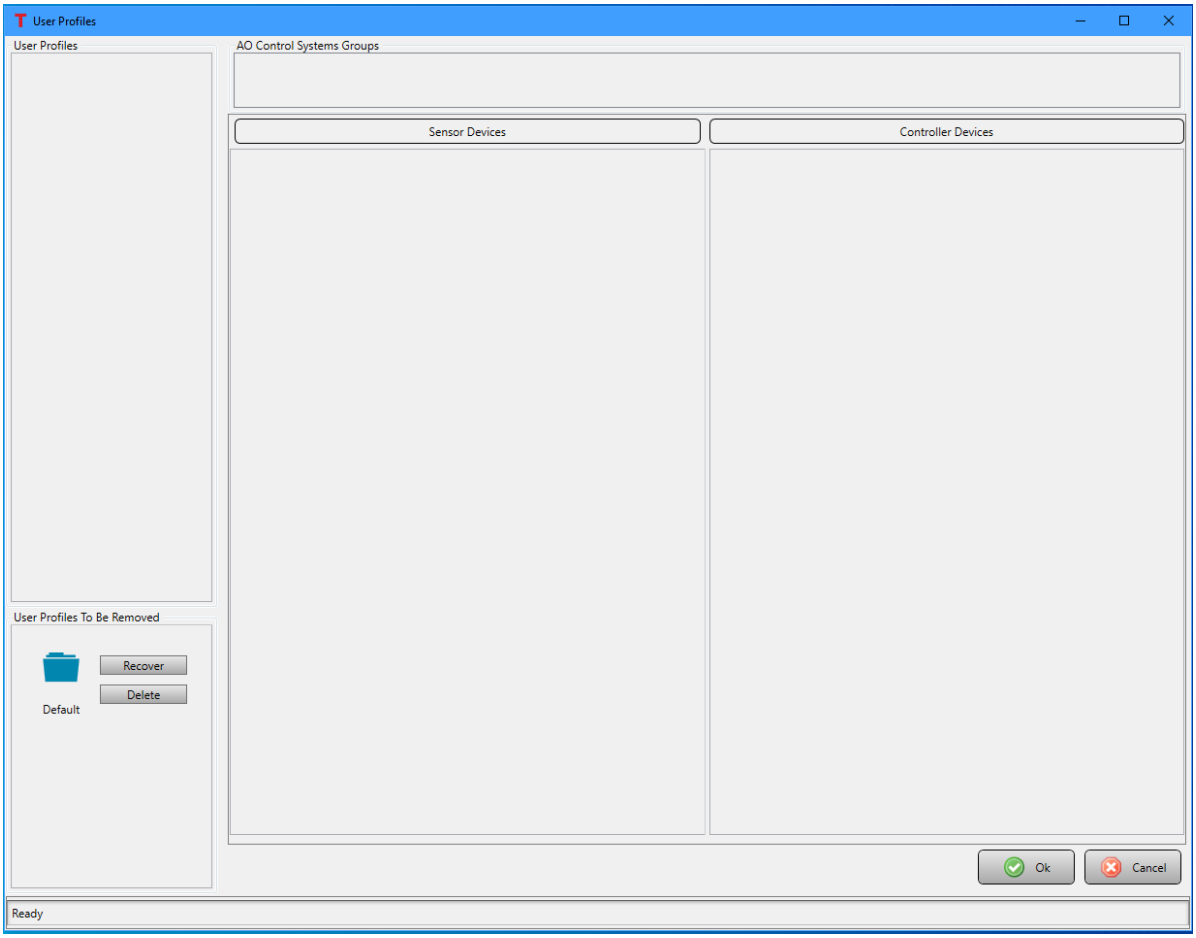


Figure 45 The User Profiles Window showing a deleted User Profile.

Click **Recover** button next to the deleted User Profile to restore the deleted User Profile.

Click **Delete** button next to the deleted User Profile to truly delete the selected User Profile from the Thorlabs Control Application. All the related configuration files and folders will be removed from the computer.

6.1.3.4. Save User Profiles

Click this button to save all the information into current user profile configuration file, which can be found at:

C:\Users\[user_name]\AppData\Roaming\Thorlabs\ThorAOControl\Application\Config\[user_profile_name].upf

6.1.4. Templates

Templates are graphical representations of the optical layout of a control system. Templates are used when creating control systems, as outlined in Chapter 7. The built-in tool to create a new template that represents a specific systems layout is accessed by clicking the **Templates** icon ( ) on the main control window toolbar, the template designer window is displayed as shown in Figure 46.

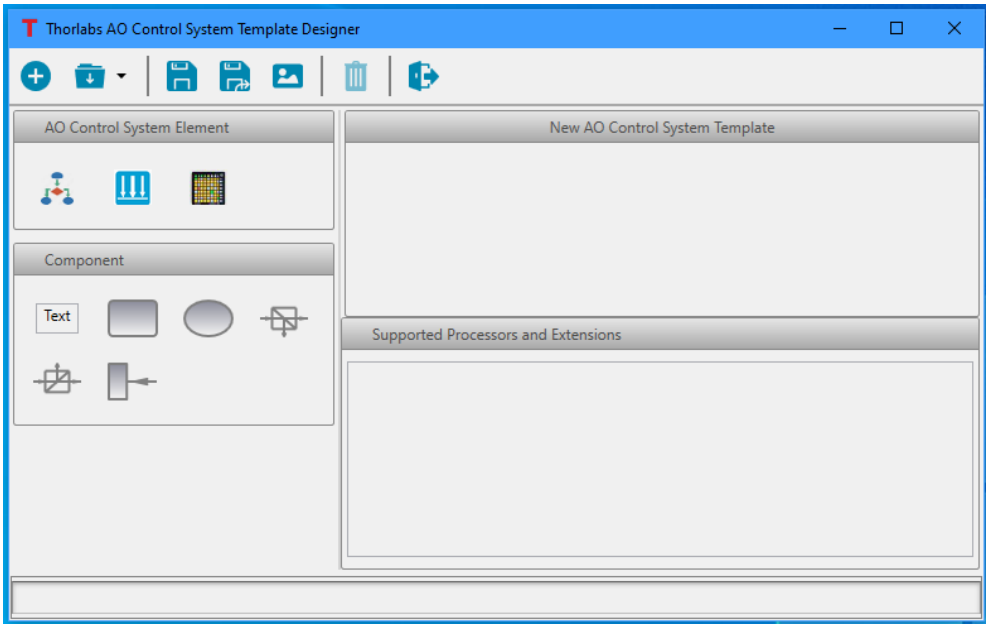


Figure 46 This window is used to create a new template, which is used when setting up a new AO control system.

AO Control System Template Designer Toolbar:



Figure 47 AO Control System Template Design Toolbar

	New Templates: Clicking this icon once one has started creating a template will erase everything to start a new template.
	Open Control System Template: Clicking this icon will show a dropdown menu with a list of available/saved templates. One may use an existing template as a starting point for a new template.
	Save Current Template: Clicking this icon will save the template with the existing opened template filename. If it is a new template, not saved already, a dialog box will pop up to select a file location and to define the file name.
	Save Current Template As: Clicking this icon will open a dialog box to select a file location and to define the file name for the new template.
	Save Current Template As Image: Clicking this icon will open a dialog box to select a file location and to define the file name for the new template. Additionally, there is a “save as type” dropdown menu with the following options: *.jpg, *.bmp, and *.png.
	Delete Current Template: When the current template is a saved template, clicking this icon will delete the template file from the folder in which it is saved.
	Exit: Clicking this icon will close the Control System Template Design window, without asking to save it.

Table 1 Definitions of the AO Control System Template Designer Window Toolbar Icons

The **AO Control System Elements** panel (Figure 48) contains the three required elements for a closed loop control system: 1) processor, 2) sensor, and 3) controller. Elements are dragged from this panel into the **New AO Control System Template** panel to create a new template.

- **Processor** - Indicated by the icon represents the closed loop control algorithm / process used to acquire a signal from a senor and determine the signal to be sent to the controller to affect a desired change.
- **Sensor** - Indicated by the icon represents the sensor being used in a closed-loop control process.
- **Controller** - Indicated by the icon represents the controller being used in a closed loop control process.

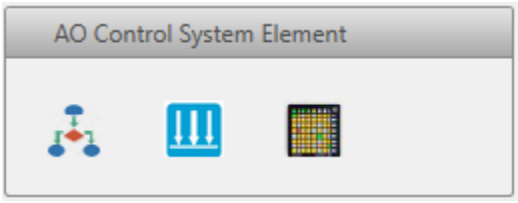


Figure 48 Graphical AO Control System Elements: Processor, Sensor, and Controller

The **Components** panel (Figure 49) contains six (6) elements that may be used to layout a custom control system: 1) a text box, 2) a rectangle, 3) an oval, 4) a beam splitter with incident beam from left and reflecting downward, 5) a beam splitter with incident beam from the left and reflecting upwards, and 6) a beam dump. Elements are dragged from this panel into the **New Control System Template** panel to create a new template.

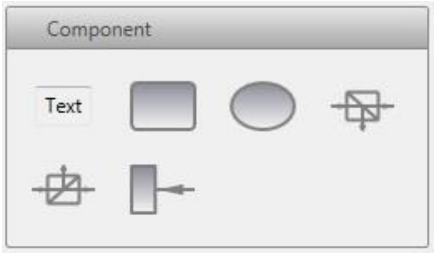


Figure 49 Graphical Elements for Creating a Custom System Template

The **New AO Control System Template** panel, the upper right panel in Figure 46, is the panel into which the various elements are dragged to create a new system template. After dragging an element into the new control system template panel, one will see nine (9) small squares: four corners, four mid-edge segments, and one off the element. An example of the rectangular element dragged into the template panel is shown in Figure 50. One of the corners is circled in red; each of the four corners may be used to scale the element by grabbing it with the cursor and dragging the cursor. One of the mid-edge segments is circled in green; each of the four mid-element points may be used to draw a line starting at the mid-element point to a mid-element point of another element. The one circled in blue may be used to rotate the element.

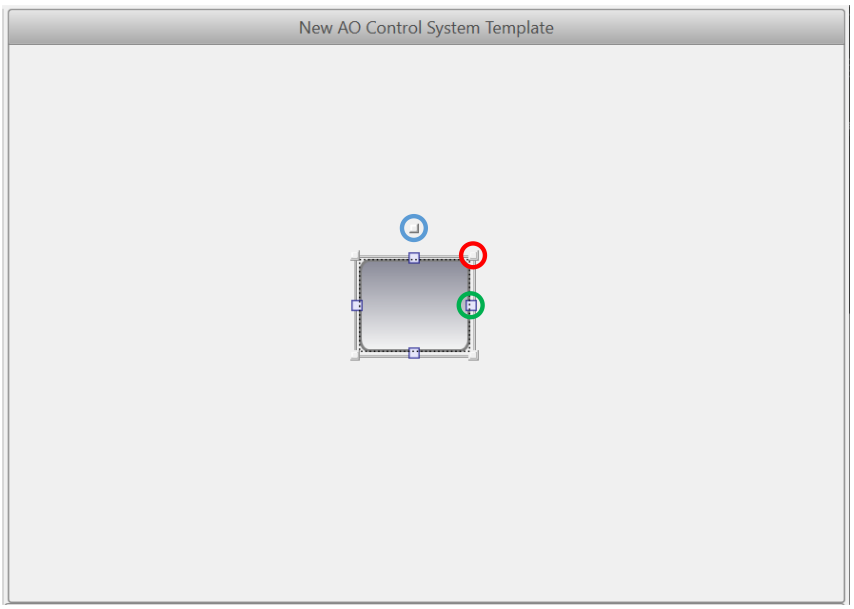


Figure 50 A graphical element can be dragged into the template panel. Corners (red) are used to scale the element, mid-line points (green) are used to draw a line from the point to another element, and the rotation point (blue) is used to rotate the element.

Using various graphical elements, a new template design can be completed, such as that shown in Figure 51. At this point, there are no processor extensions linked to the template. The processor extensions are the various processes associated with a given processor plugin module.

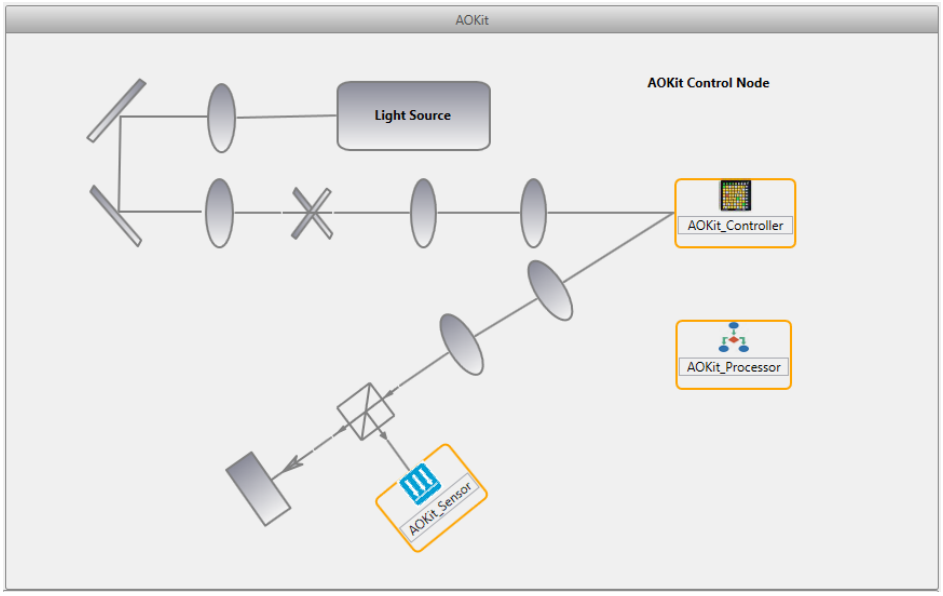


Figure 51 An example of a new system template titled AOKit System.

Right clicking into the lower right panel titled **Supported Processors and Extensions**, a small window with a single button will appear. See Figure 52. Clicking the button will bring up a Configure Template Window from which one may manage the processor / processor extensions linked to a template; see Figure 53. The configure template window will have a blank panel on the left and show the available processor modules in the right pane.

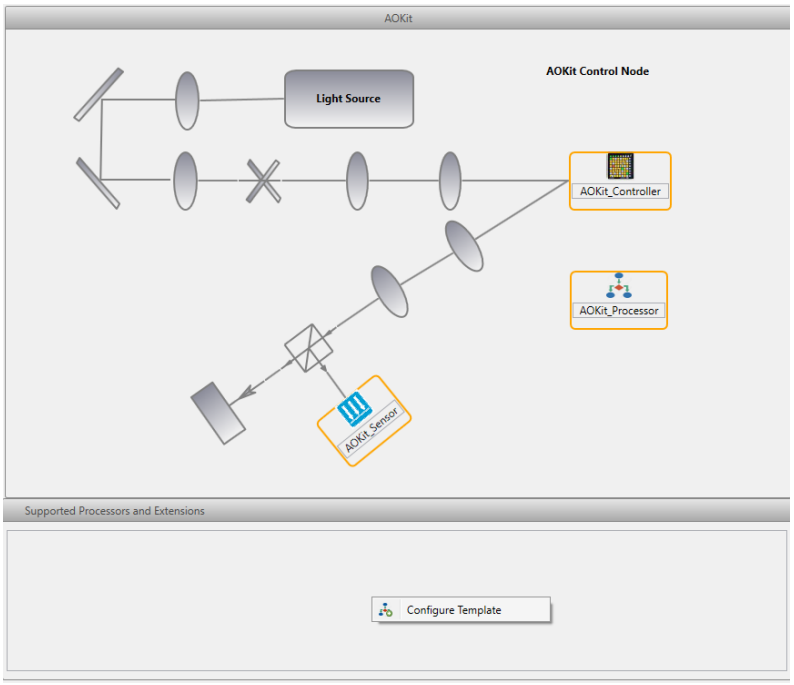


Figure 52 Right clicking into the Supported Processors and Extensions pane, lower right to bring up a button titled Configure Template. Click this to assign the processor(s) that are able to work with this template.

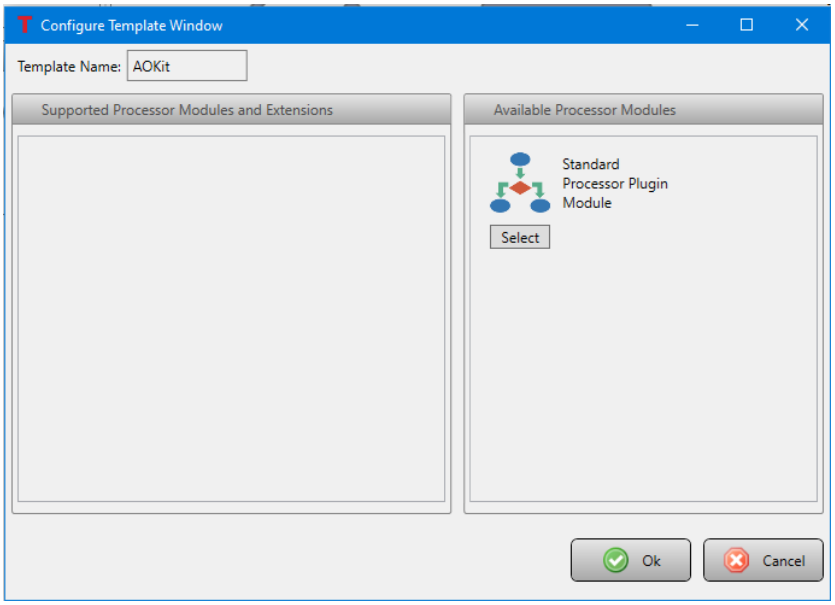


Figure 53 Configure Template window. This shows the state of the window when no process has been linked with the template.

Clicking the **Select** button under the processor module icon in the **Available Processor Modules** pane will display the processor plugin module's supported processor extensions in the pane to the left. See Figure 54. Details about the various processor extensions may be found in Section 5.3.

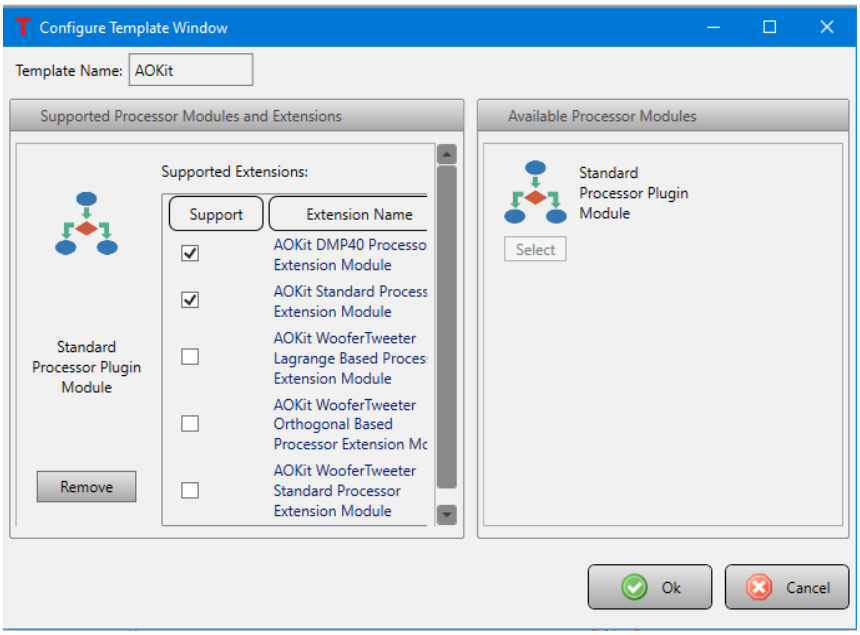


Figure 54 The Configure Template Window After the Available Processor Module at the Right is Clicked

Check all the processor extensions that are relevant to the new control system. After doing so and clicking the **Ok** button, a processor icon will appear in the **Supported Processor and Extensions** pane, and a list of the selected extensions will appear in the box to the right of the icon. See Figure 55. The new system template is now fully defined and setup for use.

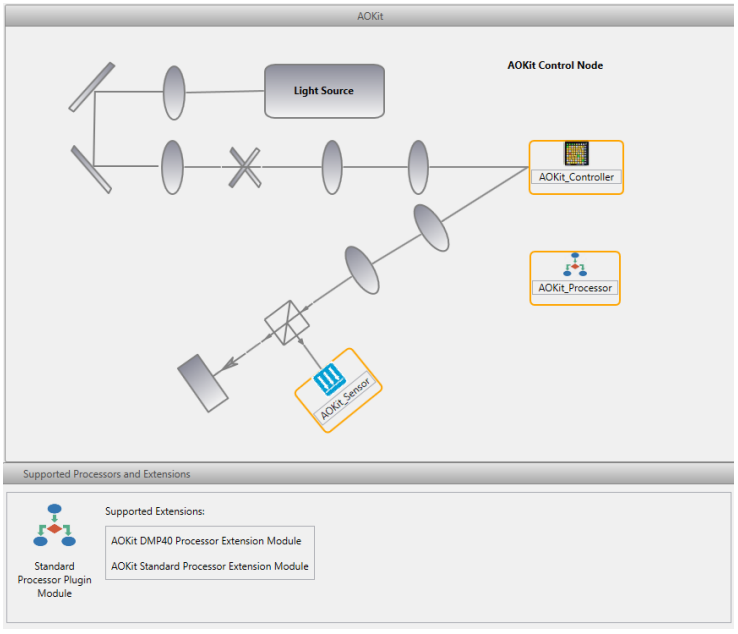


Figure 55 After processor extensions are linked to the system template, they will appear in the lower right pane.

6.1.5. Data

Data is saved in a zip file with the extension tld (Thorlabs data). The built-in data viewer reads tld files. A user may copy a tld file and change the extension to zip and extract the files to a folder if they wish to have access to the data directly. See Section 4.1 for information related to the default file location.

Clicking the **Data** icon ( ) on the main, Thorlabs AO Control Application, window will bring up a window titled Load Control System Data (Figure 56). Clicking the **Open Dataset** icon ( ) on the top Figure 56 will open a standard open file window. If the default file path is not correct, browse for the folder in which the data was recorded. After opening the file, the data will be loaded and look something like Figure 57.

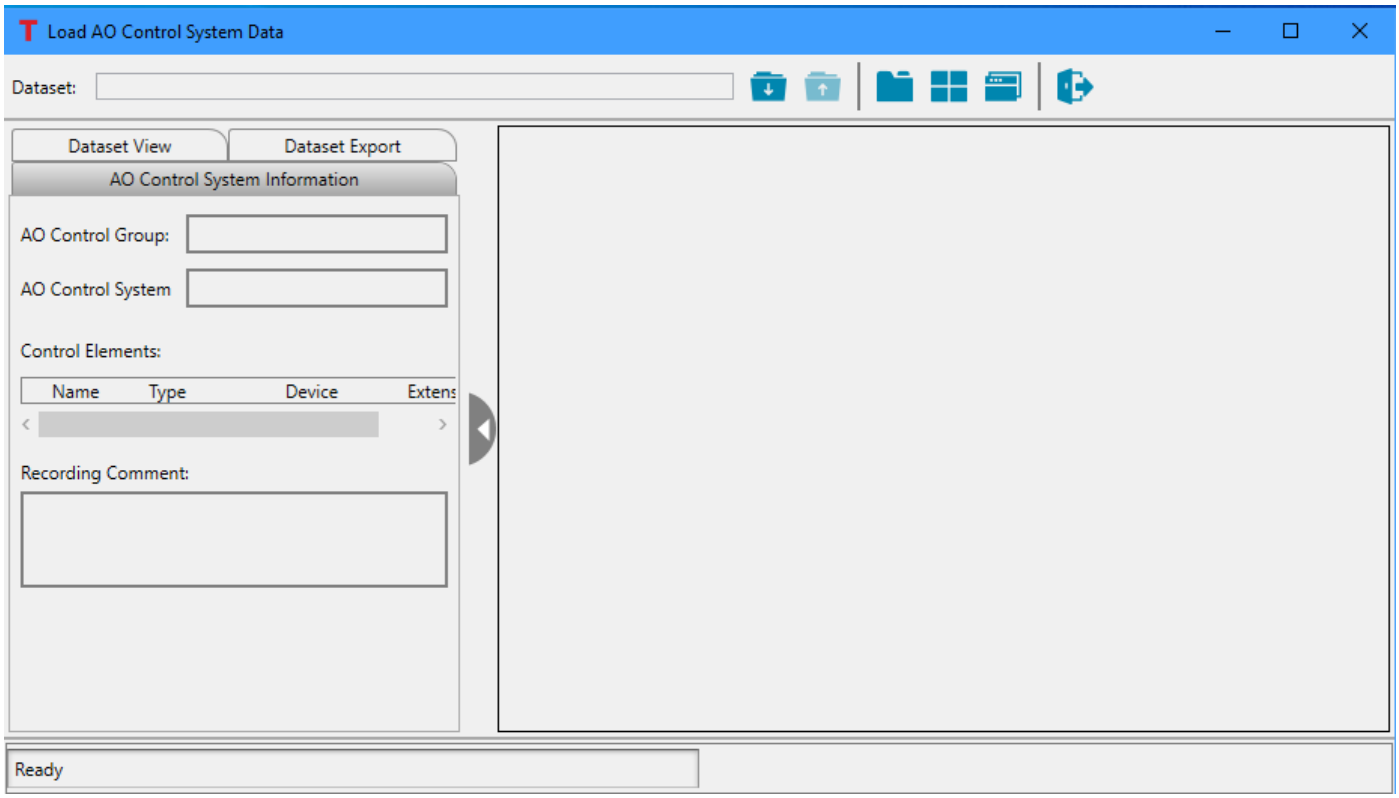


Figure 56 The Data Window allows users to view saved data.

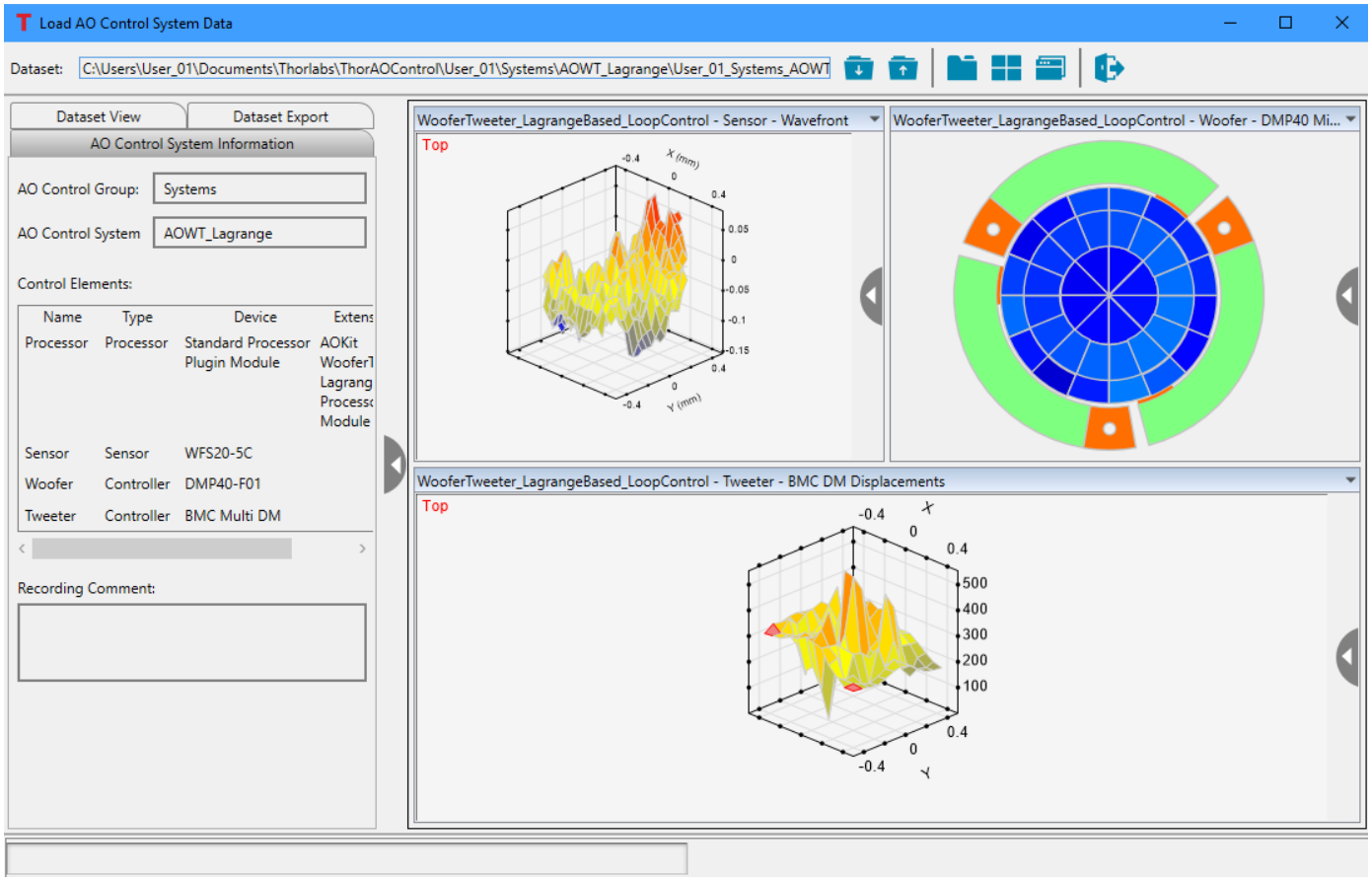


Figure 57 The Data Window showing a saved dataset. The control system information tab at the left shows details regarding the system's components.

At the left side of data window, there are three tabs: 1) **AO Control System Information**, 2) **Dataset View**, and 3) **Dataset Export**.

AO Control System Information Tab

Reference Figure 57. The **Control Group** name and **Control System** name for which the data was recorded are displayed. A region titled **Control Elements** displays details pertaining to the components of the system. A region titled **Recording Comment** displays the comments saved by the user.

Dataset View Tab

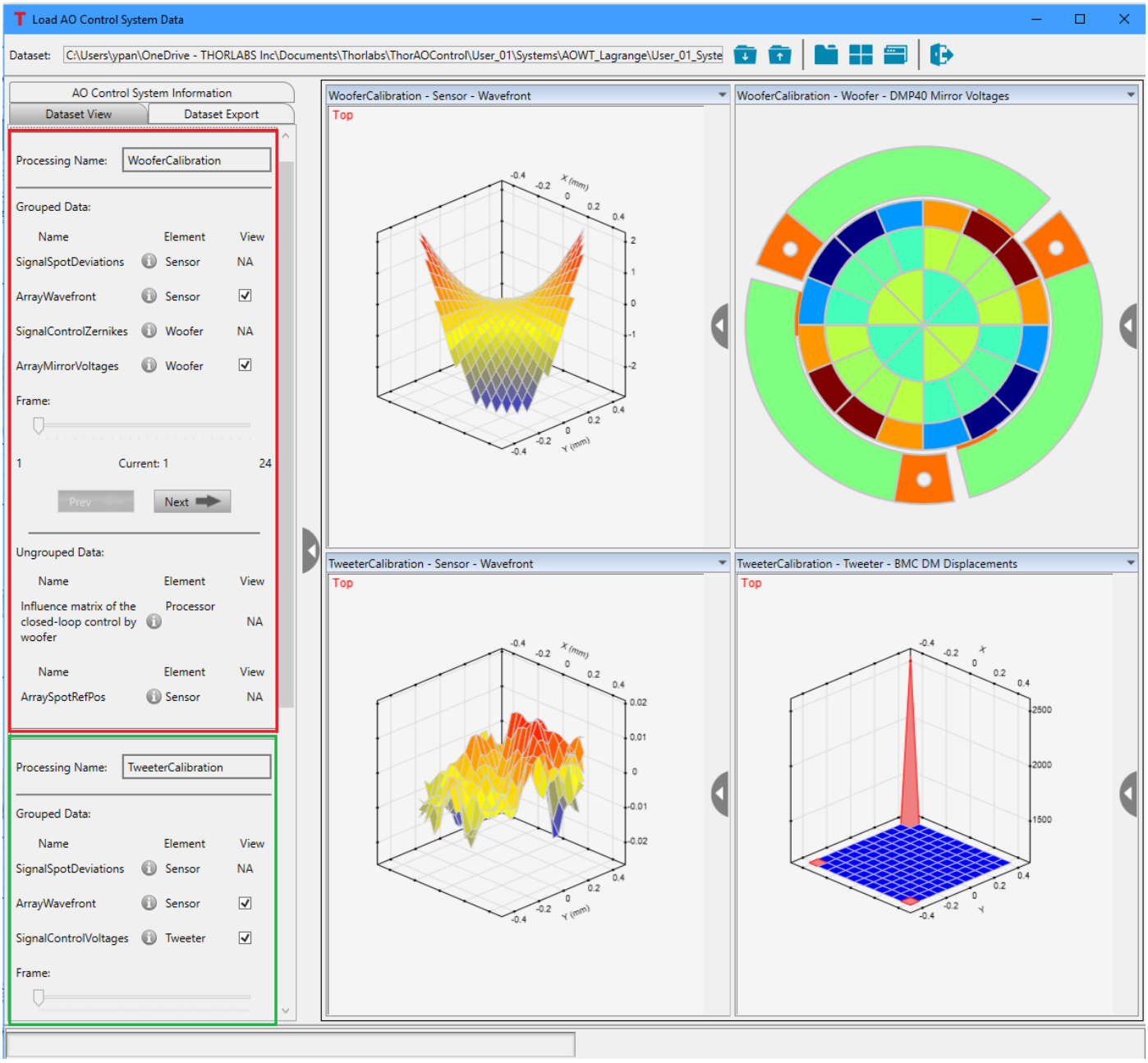


Figure 58 The Data Window showing a saved dataset. The data view tab at the left shows details regarding the recorded data.

During the recording, the data associated with the same processing will be put together. A dataset might contain a few processing procedures. For example, reference Figure 58, the loaded dataset is from the calibration of an orthogonal-based Woofer-Tweeter AO system. The calibration has three processings: WooferCalibration (red box), TweeterCalibration (partially seen in green box) and WooferTweeterCalibration (not seen in the figure). The **Processing Name** is displayed at the top, below which the possible data are divided into two groups: **Grouped Data** and **Ungrouped Data**. **Grouped Data** are recorded with the same time sequences or frame sequences and could come from different elements. **Ungrouped Data** are individual non-related data used in the measurement. The data names and element names are listed in two columns. Clicking the button ⓘ to the right of the data name will bring up a popup window and show the detail information of the data, see Figure 59.

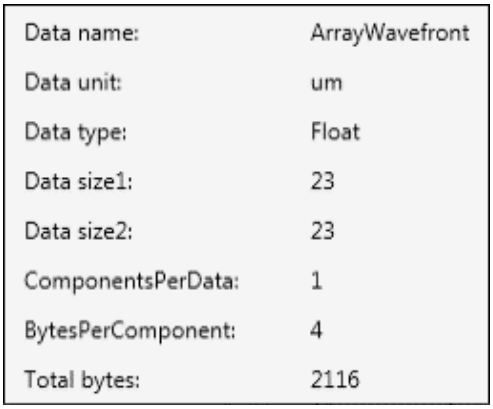


Figure 59 A popup window shows the detail information of the data.

- **Data unit**: Indicates the unit for the data.
- **Data type: Indicates the type of the data. Possible value could be:** Char**,** UChar**,** Short**,** UShort**,** Int32**,** UInt32**,** Float**,** Double **and** Unknown**.**
- **Data sizeN**: Number of data elements for the Nth data dimension. There will be one per data dimension, e.g., **Data size1**, **Data size2**, …, **Data sizeN**. Total number of data elements equals the product of all the data sizes.
- **ComponentsPerData**: This indicates the number of values per data point. One example is the wavefront spot deviation; there are two values per data point, x-deviation and y-deviation.
- **BytesPerComponent**: This indicates the number of bytes per single value of the data type indicated.
- **Total bytes**: (total number of data elements) x (components per data point) x (bytes per component)

To the right of the element name, there is a column labeled **View**. In this column there will be checkboxes for each data that was recorded. The checkboxes control whether the graphical dataset is displayed in the windows to the right.

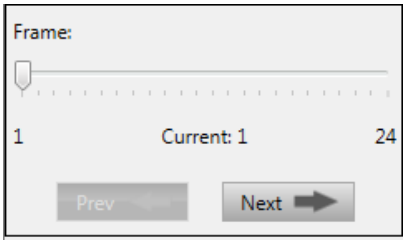


Figure 60 Data Frame Selection Controls

Below the data names and view control, there is a horizontal slider titled **Frame** (Figure 60). The displayed data in **Continuous Data** group may be changed by moving the slide control or by clicking the **Prev** or **Next** control buttons.

Dataset Export Tab

Reference Figure 61. At the top of the **Dataset Export** tab the user may select the **Export Target Directory** using the **Browse** button, which opens a standard Browse dialog enabling the user to select a directory.

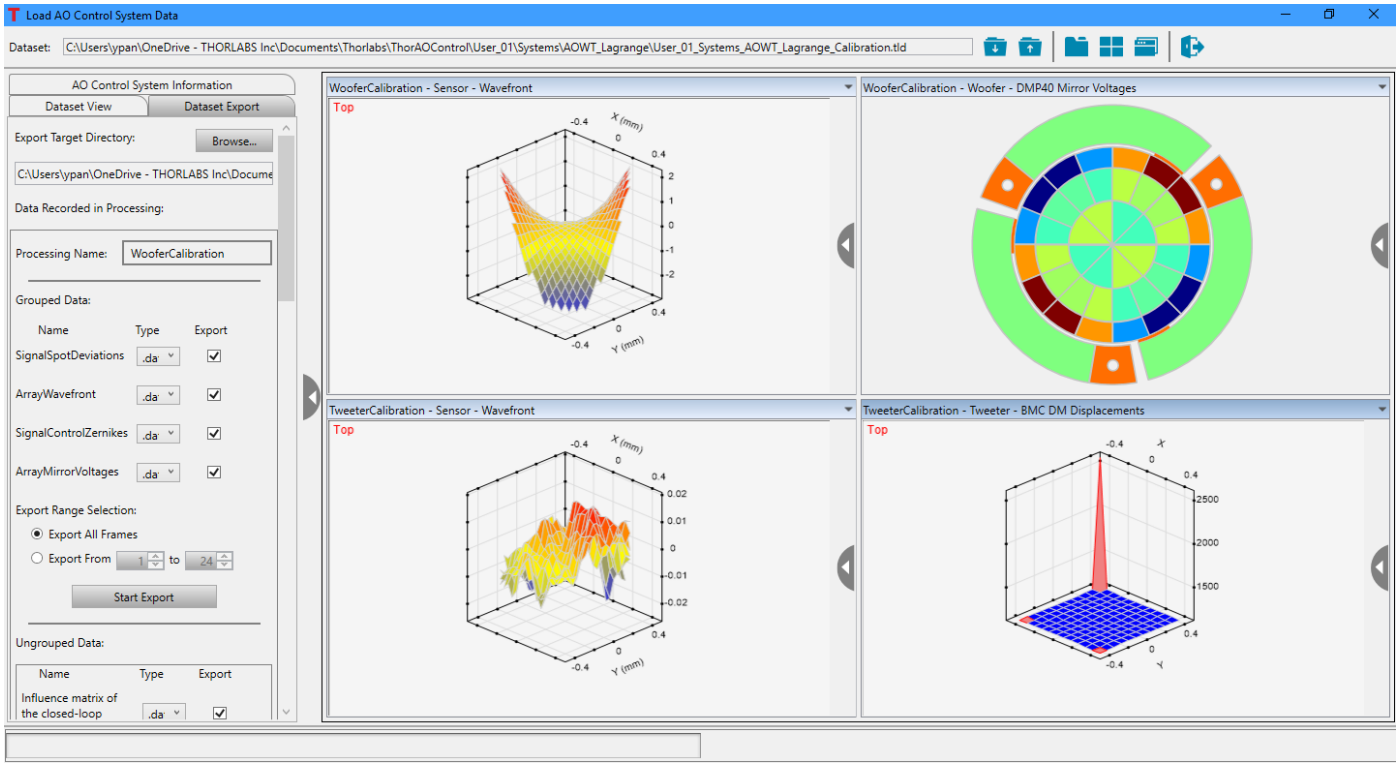


Figure 61 Data Window Showing Data Export Tab

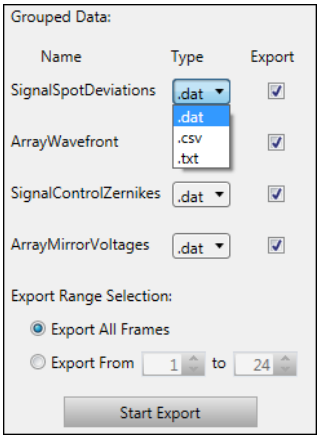


Figure 62 Data Export Options

The data can be saved to a **Binary file (.dat)**, a **Plain text file (.txt)** or a **Plain text file with comma separated values (.csv)**. The **Export** checkbox controls whether the data is included in the exportation when the button **Start Export** is clicked.

6.1.6. Tools

Clicking the Tools icon ( ) at the top of the main window displays the drop-down menu shown in Figure 63.

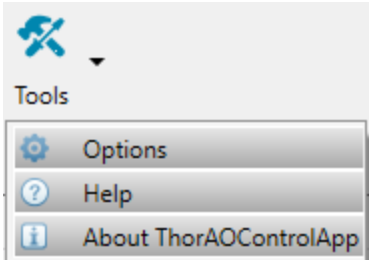


Figure 63 Tools Drop-Down Menu

- **Options** ( ) - At this time, the only general option for the user is to select the application's background theme, which may be one of two options: bright theme or dark theme. Clicking on the Options button will bring up the control system options window, shown in Figure 64. Selecting the Dark theme will result in the main application windows and all the opened child windows having a color scheme as shown in Figure 65 and Figure 66.

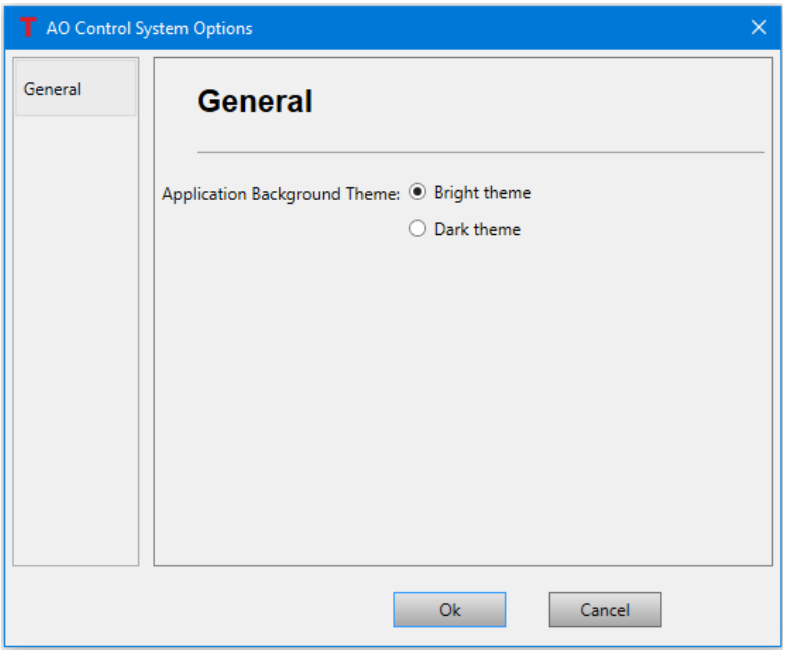


Figure 64 The AO Control System Options Window

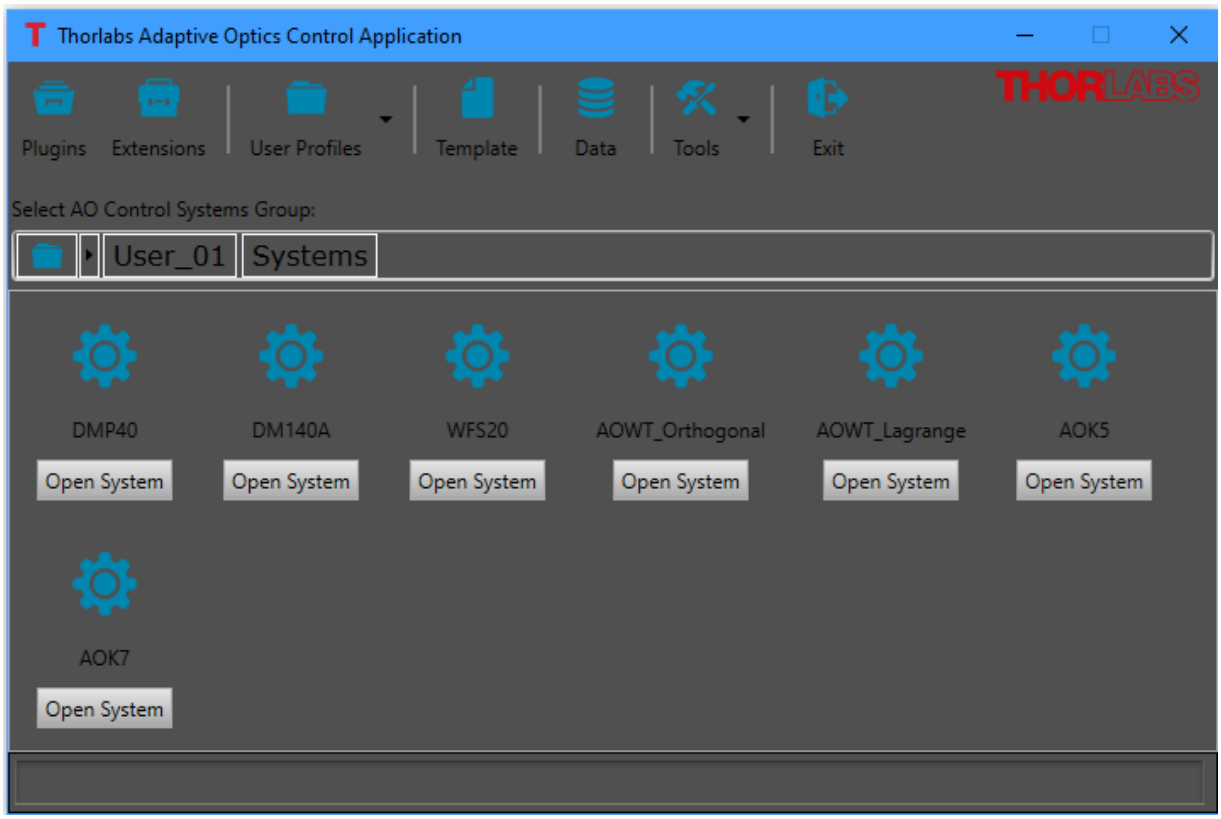


Figure 65 The Main Control Application Window with the dark theme selected.

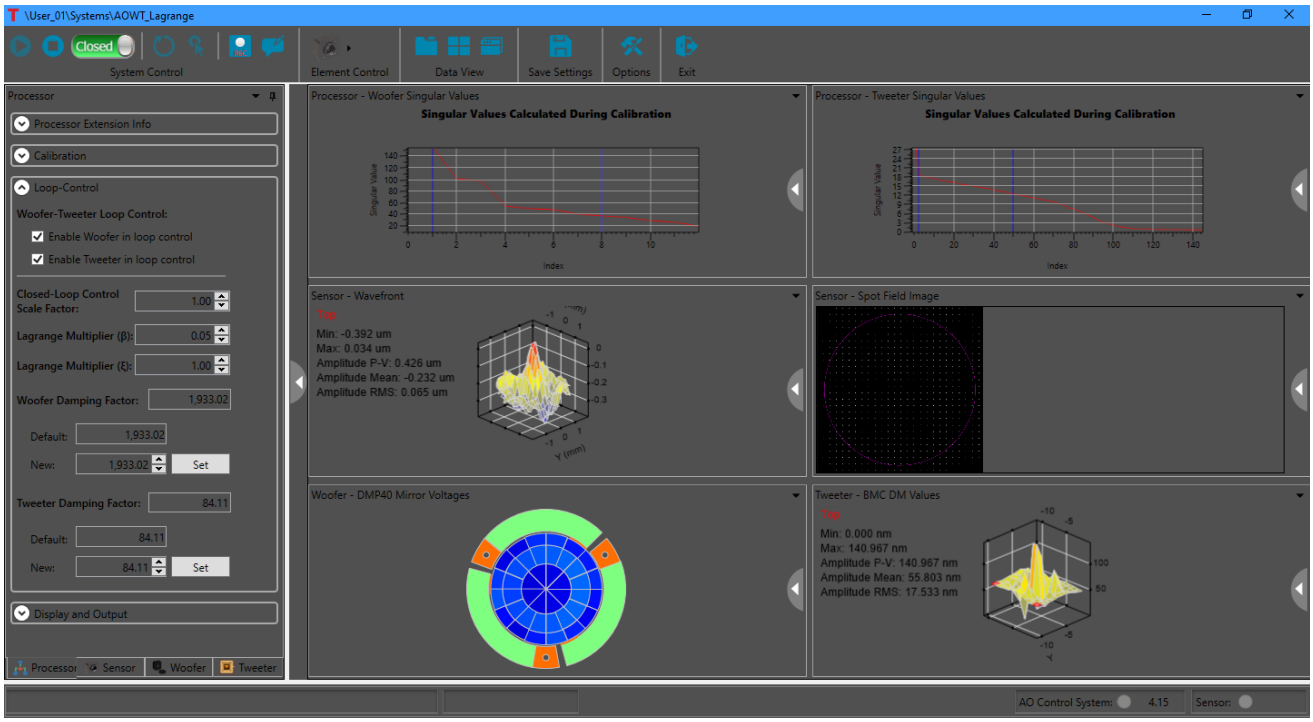


Figure 66 The Control System Window with the dark theme selected.

- **Help** (?) – Clicking on Help button opens this manual.

- **About ThorAOControlApp** ( ) –The About window, as shown in Figure 67, gives Thorlabs' contact information and also provides the information about installed software, plugin and extension module version, and the connected devices. When the DM and the SH devices are found, their information, such as model and serial numbers, will be displayed. Please have this information ready when contacting Thorlabs for technical support.

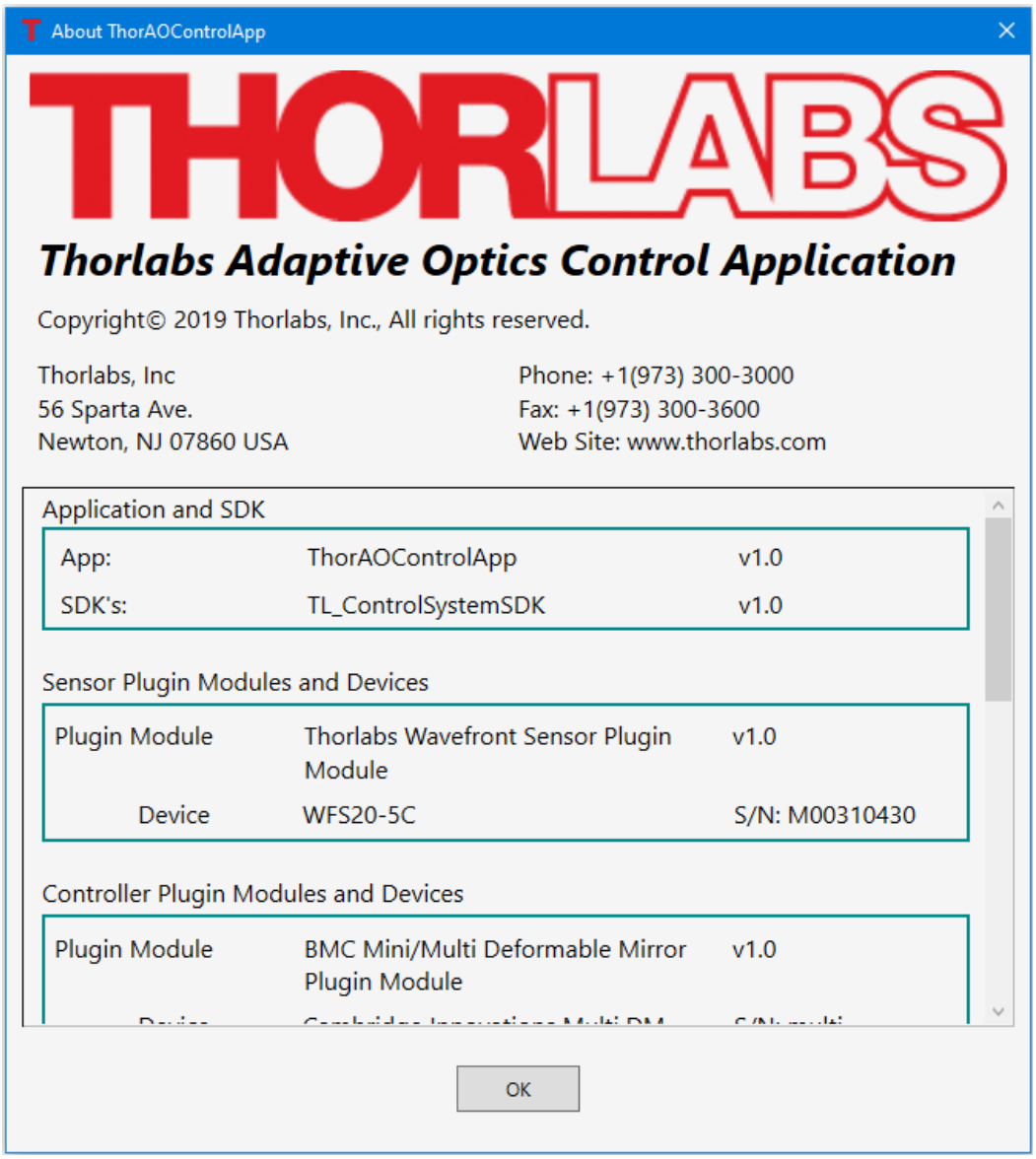


Figure 67 About Window

6.1.7. Exit

To exit / close the Thorlabs Control Application, click the **Exit** button icon (on the main control system window toolbar. If a control system is open, running or not, clicking the **Exit** button will close the open system window(s) and then terminate the main application window. Upon exiting, all of the settings related to the plugins and extensions used in the open system(s) will be saved.

6.1.8. Quick Link to Thorlabs Website

Click the Thorlabs icon in the toolbar to open the Thorlabs website:

6.2. User Profiles and Control Systems Group

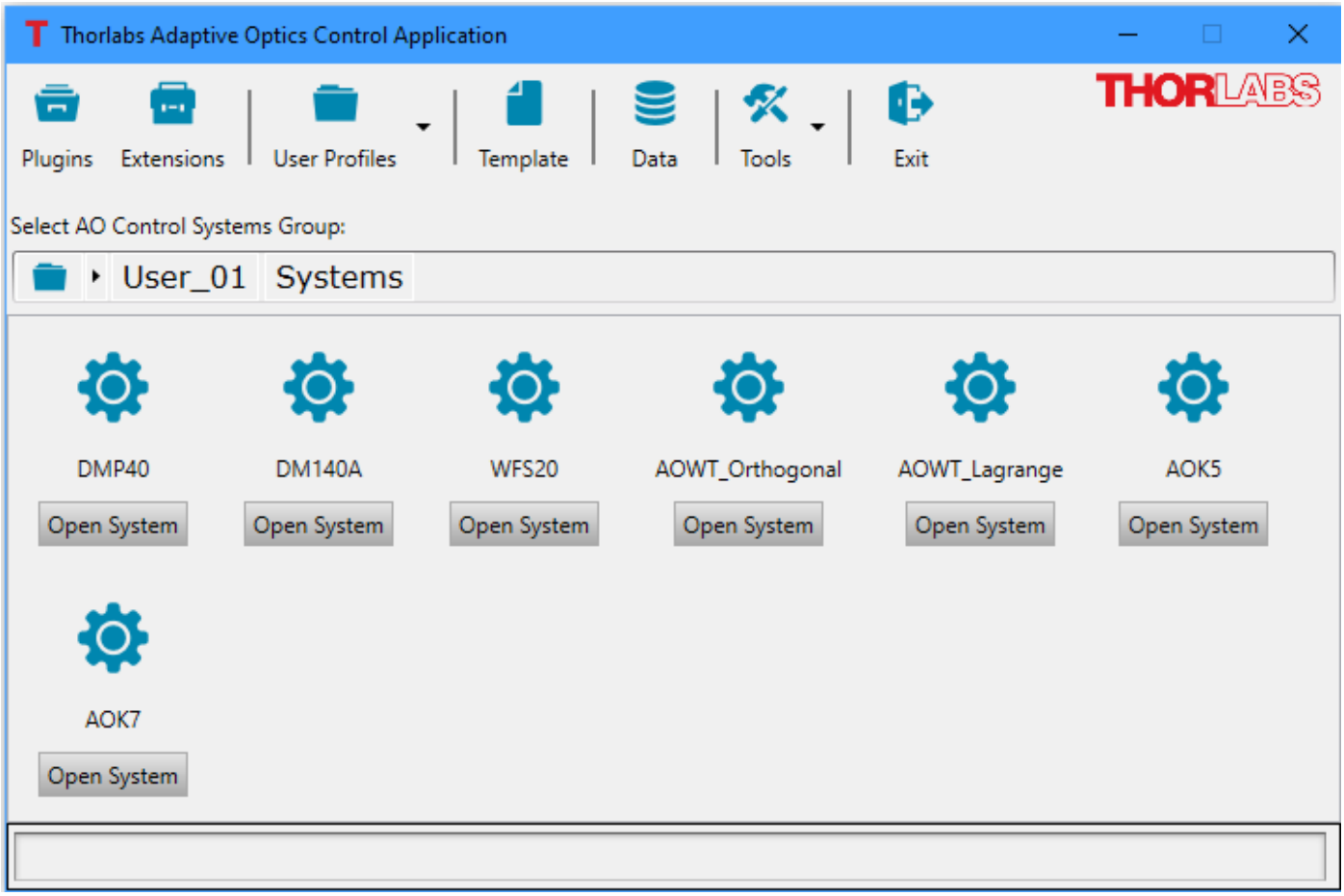
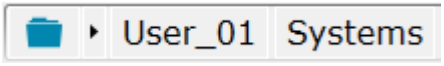


Figure 68 User Profiles and Control Systems Group

Select Control Systems Group: 

The two-level breadcrumb navigation, User Profile/Control Group, allows users to select different user profiles and control groups. All the control systems in the selected User Profile/Control Group are displayed underneath. Click the **Open System** button under a control system icon ( ) to run the selected control system. If the **Open System** button is disabled, hovering the cursor over the disabled button will show the possible reasons which cause the button to be disabled, as shown in Figure 69.

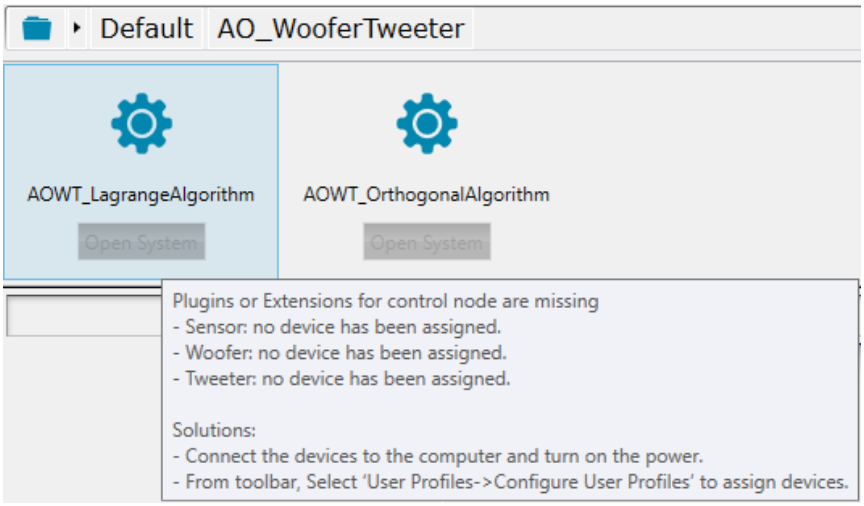


Figure 69 Hovering the cursor over the disabled Open System button to show the possible causes for disabling the button.

6.3. Status Bar

The **Status Bar** on the bottom of the Main GUI shows the current status of Thorlabs AO Control Application.

Chapter 7 Configure User Profile

This chapter presumes a User Profile exists. If not, see Section 6.1.3 for instructions to create a User Profile. After creating the user profile, user can add control groups and control systems to the user profile. A control system may be a wavefront sensor, a deformable mirror, a single DM / single WFS AO system, or a dual DM / single WFS Woofer-Tweeter AO control system. Control System Groups may be used to group various systems. Only systems within the same Control System Group may be run simultaneously.

7.1. Configure Default User Profile

As mentioned in 6.1.3.1, the default user profile has pre-defined control groups and control systems with devices not assigned yet. To assign the devices to the control systems:

1. From main window toolbar, click User Profiles->Configure User Profiles. This will open User Profiles window, see Figure 70.

2. To rename the user profile, click **Rename** button within the highlighted User Profile.

3. To assign the devices to the control systems, click the **Configure** button within the highlighted User Profile. This will open the **Configure User Profile** window shown in Figure 71.

4. From **AO Control Systems Groups** panel, select the desired control system to which the devices will be assigned.

5. Use one of the following steps to add a sensor device, see Figure 72:

   - Below the Sensor Devices category, click the Select Plugin button, blinking orange/grey, and select the desired sensor from the list of available sensors.

   - Or in the template figure, right-clicking Sensor element, blinking orange/grey, brings up a context menu. Click Select Plugin and select the desired sensor from the list of available sensors.

6. Use one of the following steps to add a controller device, see Figure 72:

   - Below the Controller Devices category click the Select Plugin button, blinking orange/grey, and select the desired controller from the list of available controllers (deformable mirrors).

   - Or in the template figure, right-clicking Controller element, blinking orange/grey, brings up a context menu. Click Select Plugin and select the desired controller from the list of available controllers (deformable mirrors).

7. Click the **Ok** button to close the window, which will update the User Profile window to include the details about the devices linked to new system. See Figure 73.

8. Clicking the **Ok** button in the User Profile window will cause the Main window to update. For the control systems that have all the devices assigned, the **Open System** button is now enabled, and the system is ready to run. See Figure 74.

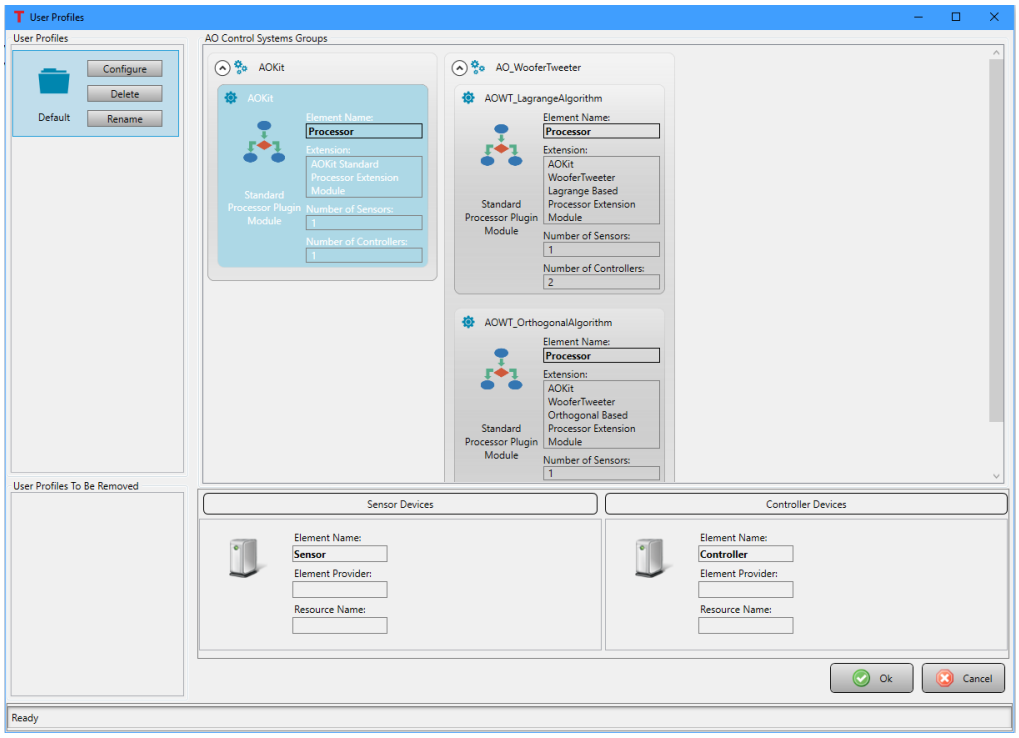


Figure 70 This window appears after clicking the Configure User Profiles from Main window.

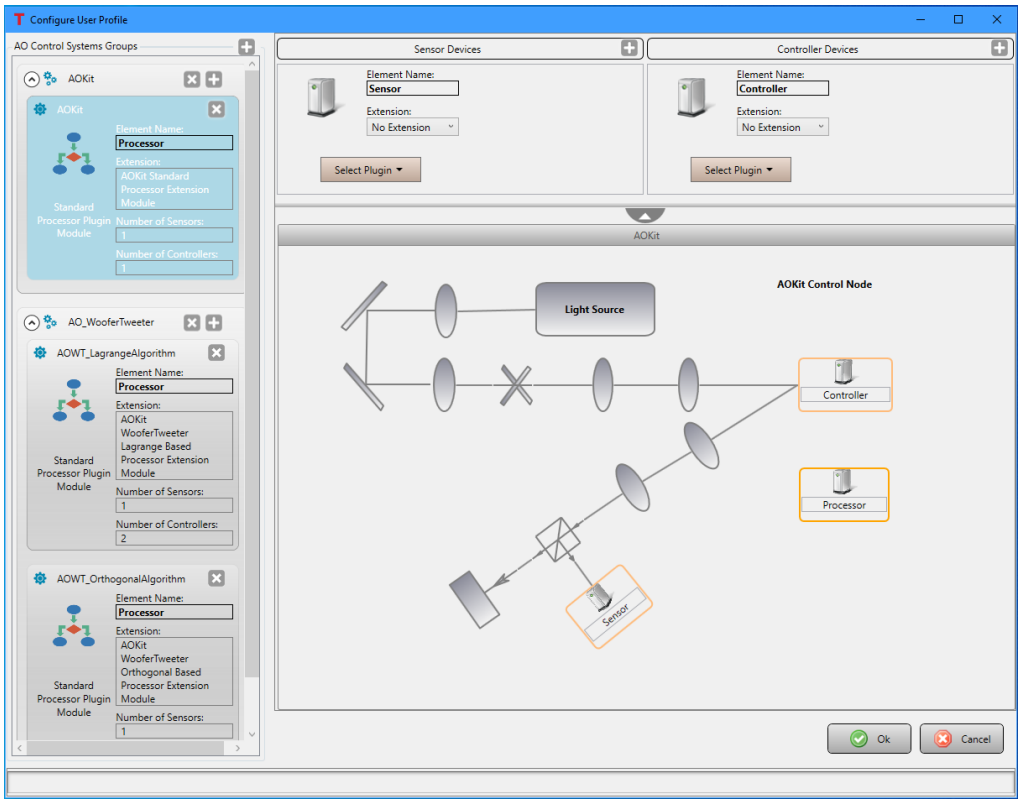


Figure 71 This window appears after clicking the Configure option within a highlighted User Profile.

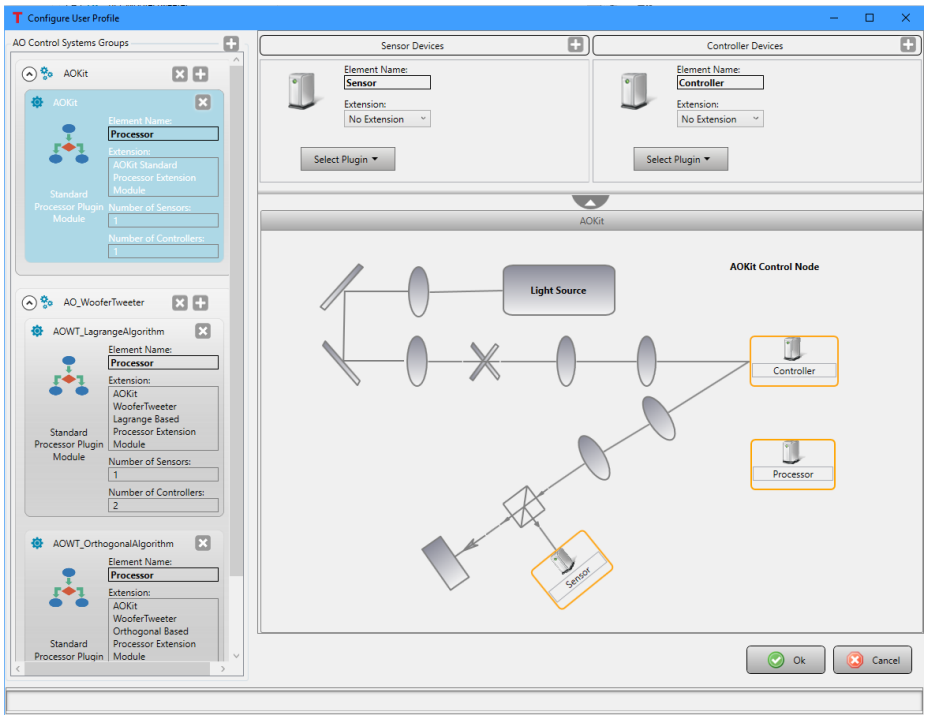


Figure 72 The Configure User Profile Window is showing a newly created system titled AOKit. No sensor or controller has been selected. A conceptual layout is displayed in the lower right of the window, providing a graphical representation of the system.

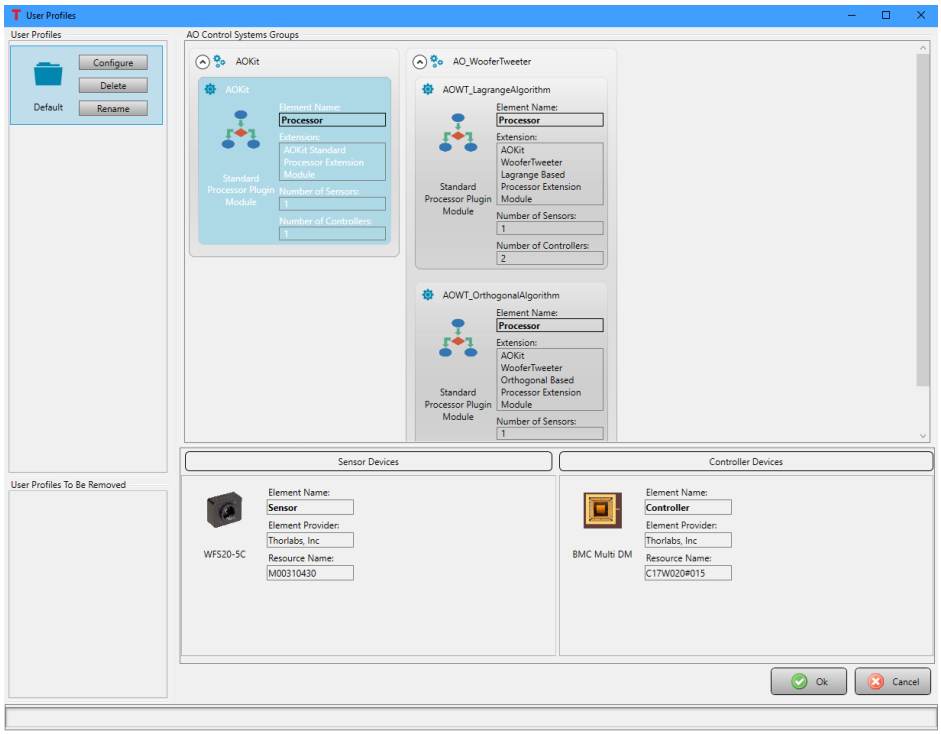


Figure 73 With the AOKit control system highlighted, the details related to the linked devices are displayed under the Sensor Devices and Controller Devices headings.

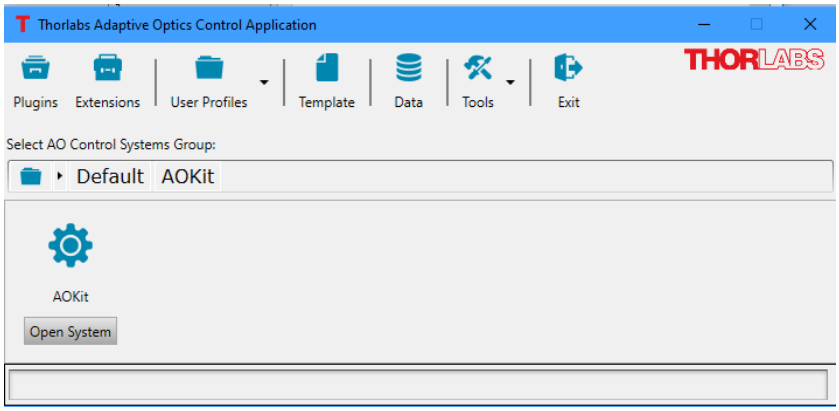
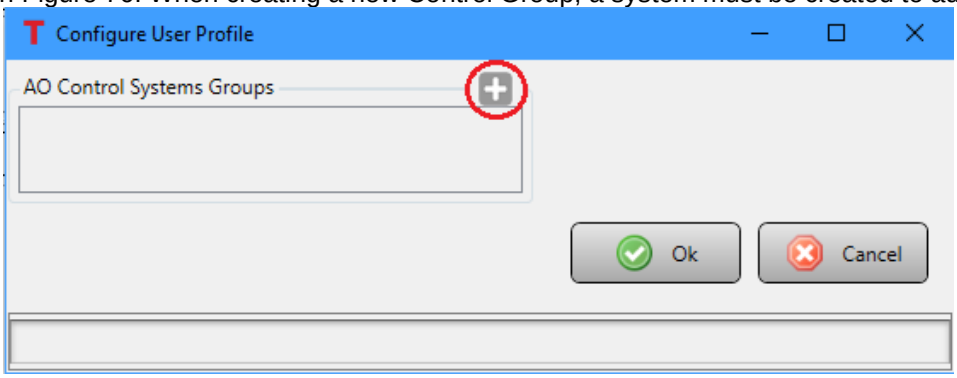


Figure 74 The Main Window Showing a Newly Configured System Titled AOKit within the User Profile Default and Group AOKit

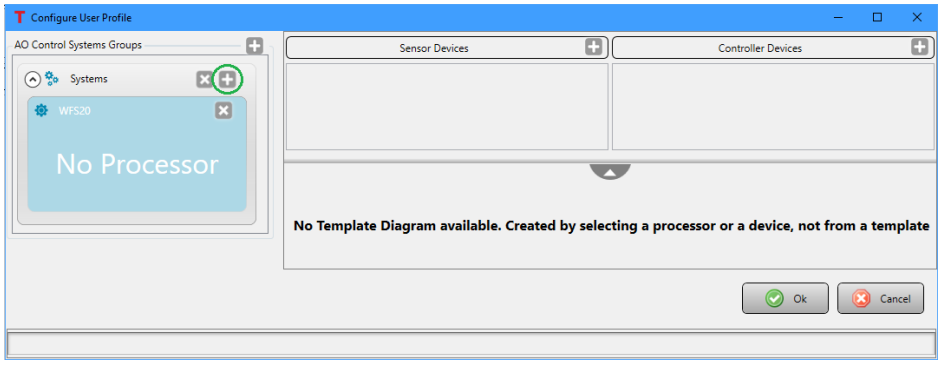
User can follow the same steps to assign the devices to control system AOWT_LagrangeAlgorithm and AOWT_OrthogonalAlgorithm.

7.2. Create Control Group and Control System

To add a Control System Group to a User Profile, click the **Configure** button within the highlighted User Profile. This will open the **Configure User Profile** window shown in Figure 75. Click the '+' icon ( ) in red circle to the right of the **Control Systems Groups** title, as shown in Figure 75(a), to open the **New Control Group/System** Window shown in Figure 76. When creating a new Control Group, a system must be created to add to the group.



(a) Creating a new Control Group



(b) Add a new Control System to an existing Control Group

Figure 75 This window appears after clicking the Configure option within a User Profile.

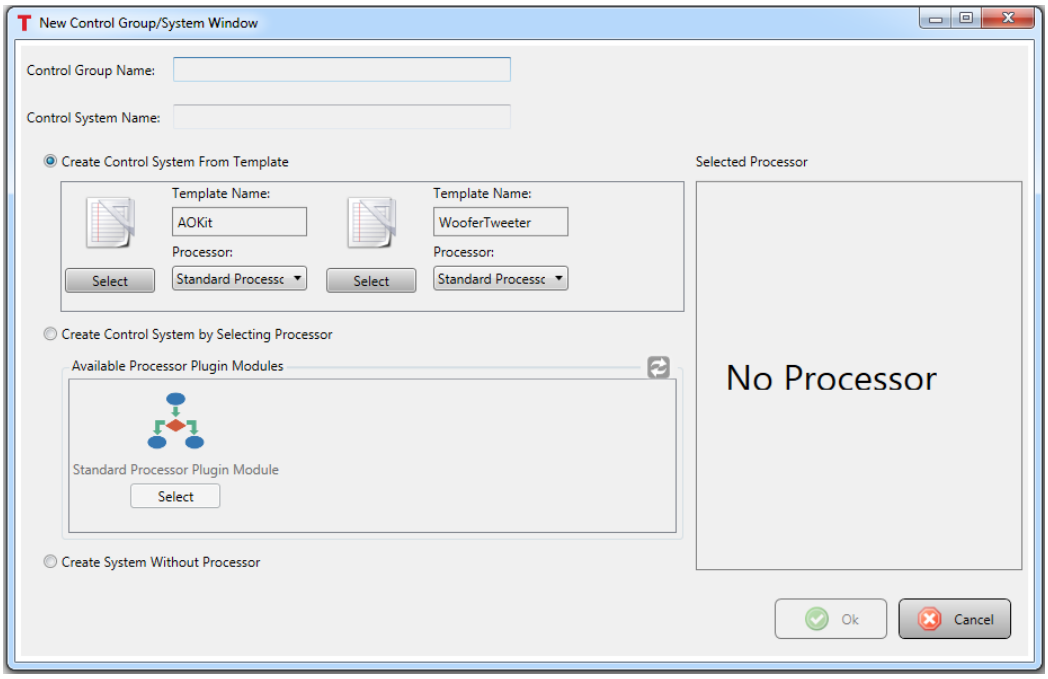


Figure 76 The New Control Group/System Window

If adding a system to an existing Control System Group, click the '+' icon ( ) in green circle to the right of the name of an existing group, such as the one titled **Systems** in Figure 75(b), to display the **New Control System** window, Figure 76.

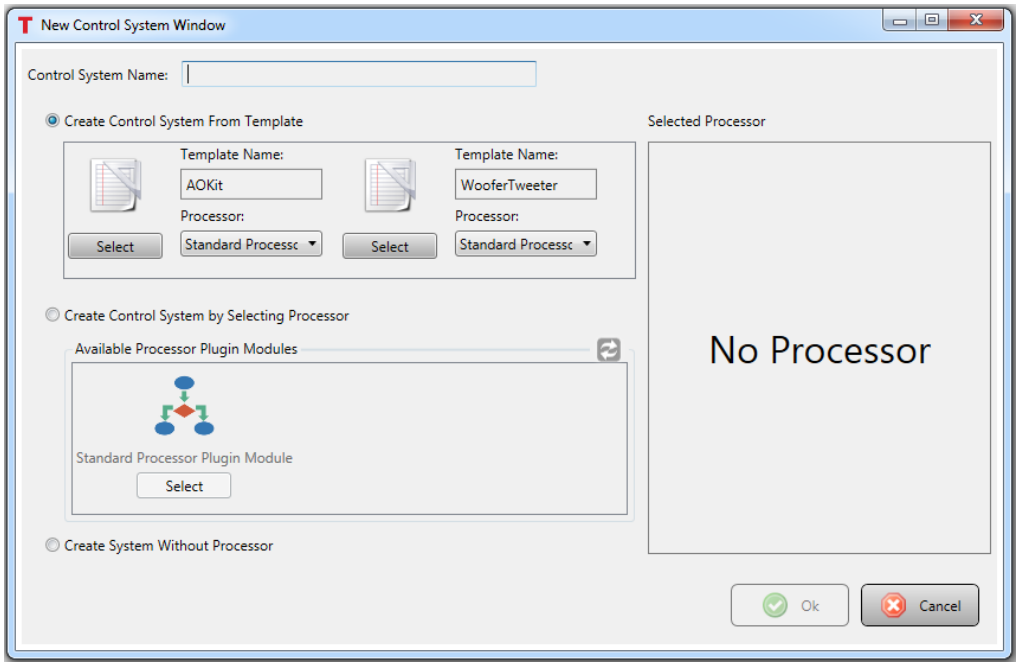


Figure 77 The New Control System Window

Clicking the 'X' icon ( ) to the right of a Control Group name will delete the group from the available Control System Groups. Clicking the 'X' icon ( ) to the right of a Control System name will delete the system from the Control Group.

7.2.1. Creating a Device Only System

To create a device only system, which would allow a sensor or a controller to be run independently:

1. Add a name for the system into the New Control Group/System window (Figure 76) or the New Control System window (Figure 77).

2. Click the button to the left of the **Create System Without Processor** option (bottom of the windows).

3. Click the Ok button to continue. This will update Configure User Profile window, showing the newly created system. Figure 78 shows the Configure User Profile window, with a newly created device only system titled WFS20 within the Control System Group titled Systems. The WFS20 system is labeled with No Processor, indicating it is a device only system. There is no device linked to the system, evident with no sensor or controller device listed under either category on the right side of the window in Figure 78.

4. To add a device, click on the '+' icon ( ) to the right of the **Sensor Devices** or **Controller Devices** category. This will show a list of available sensors or controllers attached to the system. Select the one to be linked with the newly created device only system. Doing so will add the device to the area below the **Sensor Devices** or **Controller Devices** heading, see Figure 79.

5. Click the Ok button to close the window, which will update the User Profile window to include the details about the device linked to the device only system. See Figure 80.

6. Clicking the Ok button in the User Profile window will cause the Main window to update. An icon will appear in the lower section of the window when the Control System Group within the User Profile within which the system was created is selected. See Figure 81.

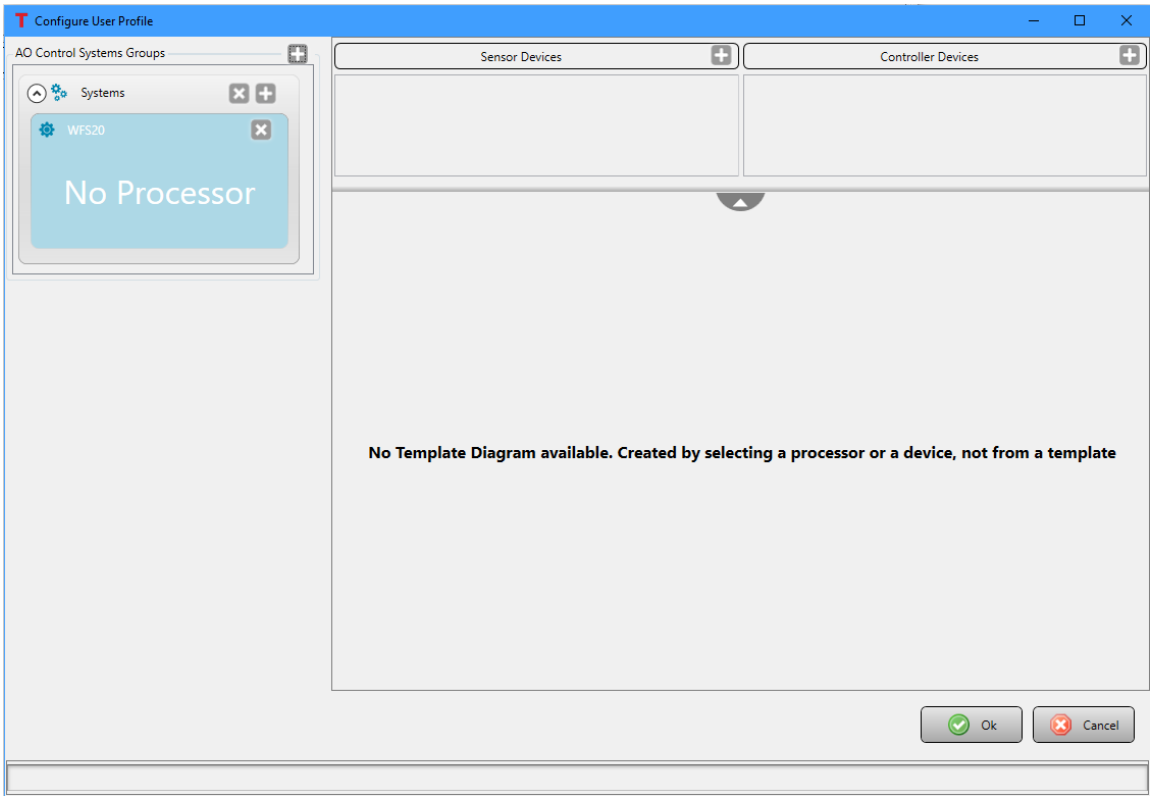


Figure 78 The Configure User Profile window is showing a newly created system titled WFS20. This is a device only system; no processor is linked to the system.

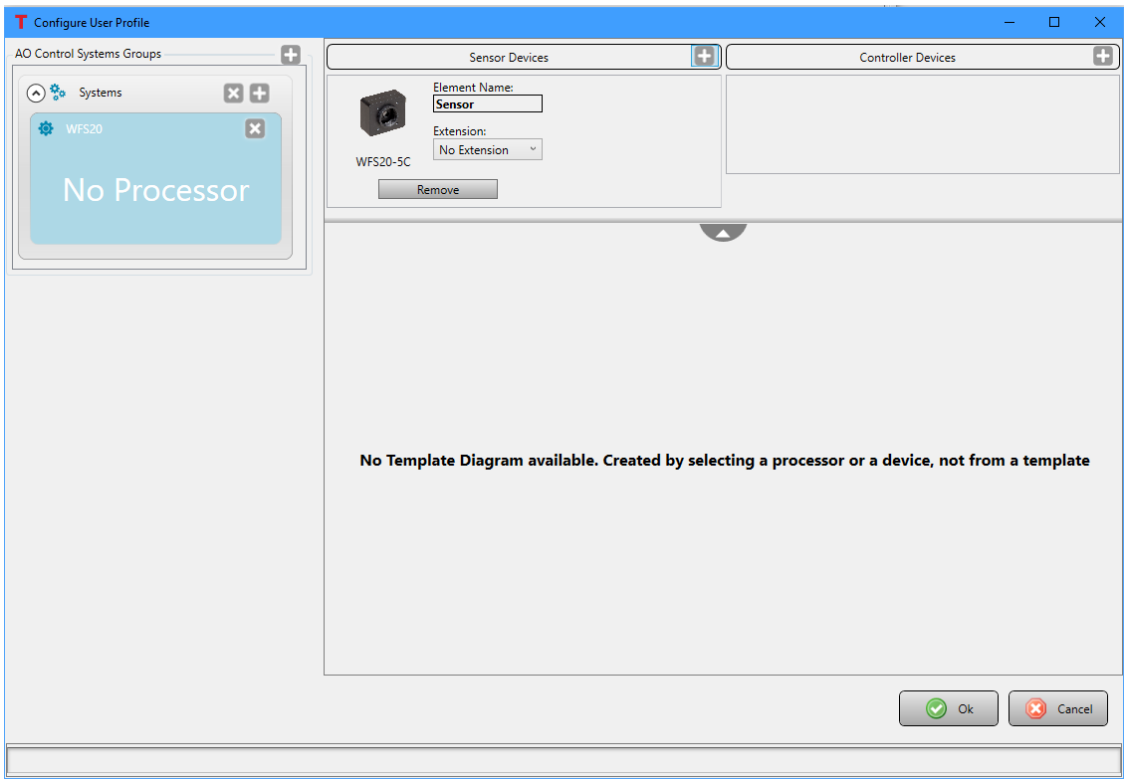


Figure 79 The Configure User Profile window is showing a newly created system titled WFS20. The linked device WFS20-5C is selected.

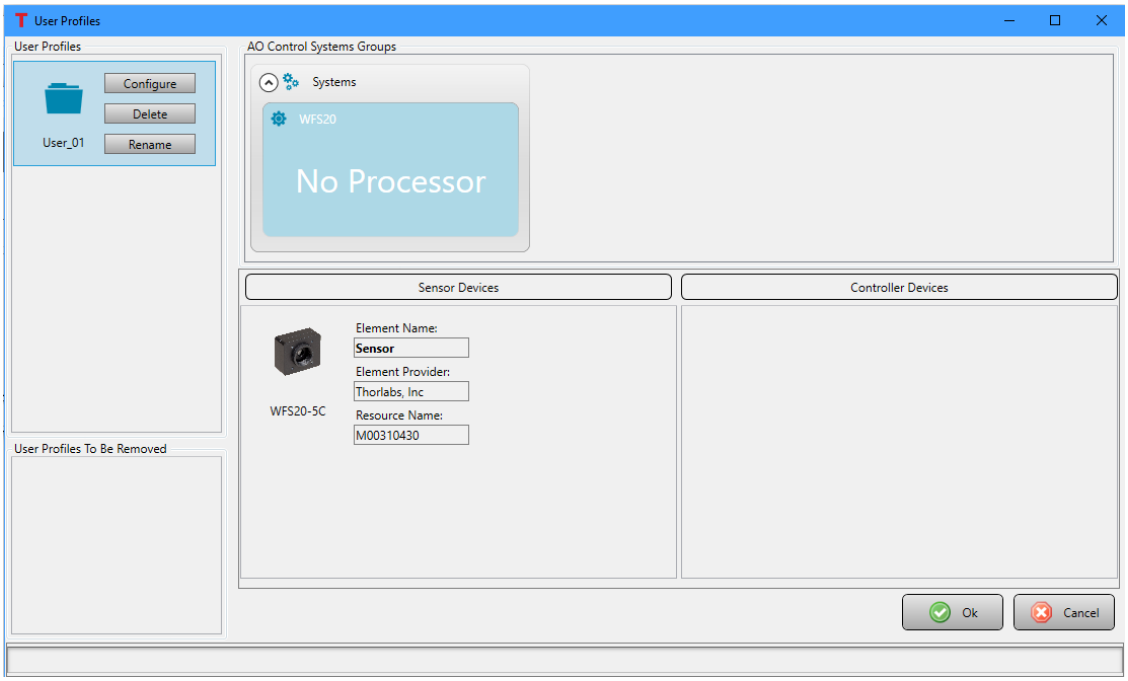


Figure 80 The User Profile window is showing a newly created system titled WFS20. This is a device only system; no processor is linked to the system. With the WFS20 sensor system highlighted, the details related to the linked device are displayed under the Controller Devices heading.

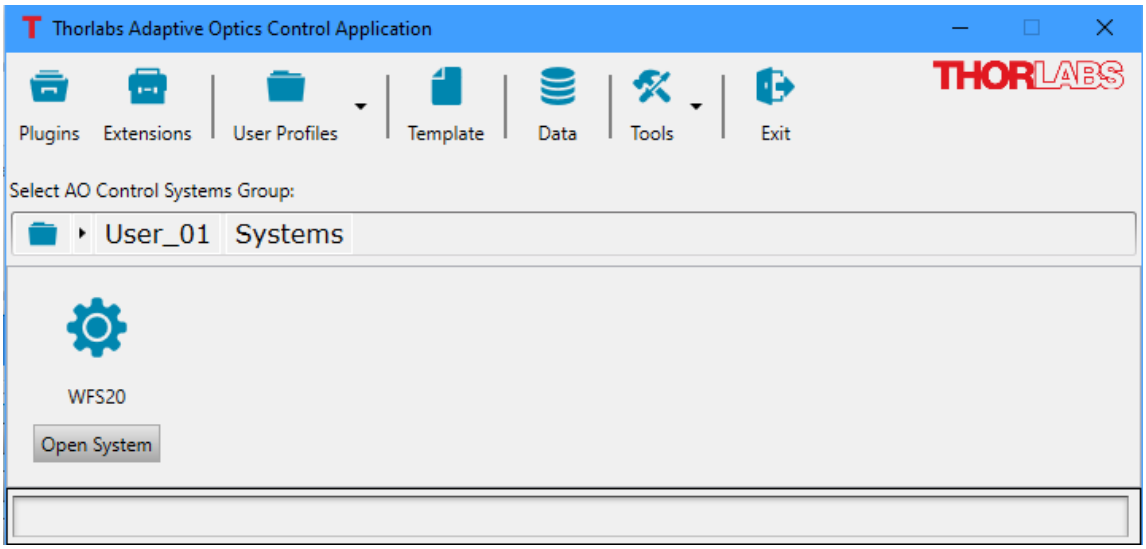


Figure 81 The Main Window Showing a Newly Created System Titled WFS20 Within the User Profile User_01 and Control System Group Systems

7.2.2. Creating a DM-WFS AO Control System

To create a single deformable mirror / single wavefront sensor AO control system:

1. Add a name for the system into the New Control Group/System window (Figure 76) or the New Control System window (Figure 77).

2. Click the button to the left of the **Create System From Template** option. Then select the template named AO Kit. A processor will appear in the **Selected Processor** box at the right side of the window. See Figure 82. There is a dropdown menu under the Extension option for the processor; from this menu, select the processor extension to use with the AO control system. Two options are available: AO Kit DMP40 Processor Extension Module and AO Kit Standard Processor Extension Module. See Section 5.3 for details about these two options.

3. Click the **Ok** button to continue. This will update Configure User Profile window, showing the newly created system. Figure 83 shows the Configure User Profile window, with a newly created system titled AOK5 within the Control System Group titled Systems. The AOK5 system displayed within the Control Systems Groups section at the left of the window shows the processor extension name (AO Kit Standard Processor Extension Module in this example), and the number of sensor and controllers supported by the processor extension is noted. There are no devices linked to the system, evident with no sensor or controller device listed under either category on the right side of the window.

4. Follow step 5 in 7.1 to select sensor device.

5. Follow step 6 in 7.1 to select controller device.

6. Click the **Ok** button to close the window, which will update the User Profile window to include the details about the devices linked to new system. See Figure 84.

7. Clicking the **Ok** button in the User Profile window will cause the Main window to update. An icon will appear in the lower section of the window when the Control System Group within the User Profile within which the system was created is selected. See Figure 85.

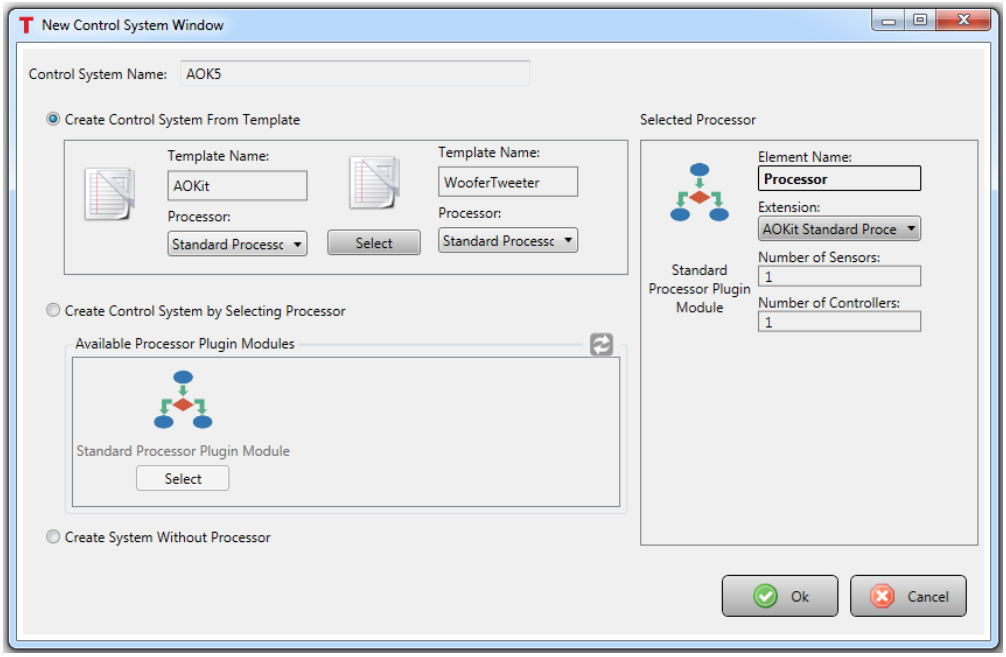


Figure 82 The New Control System Window Showing Two Options Under the Create Control System From Template

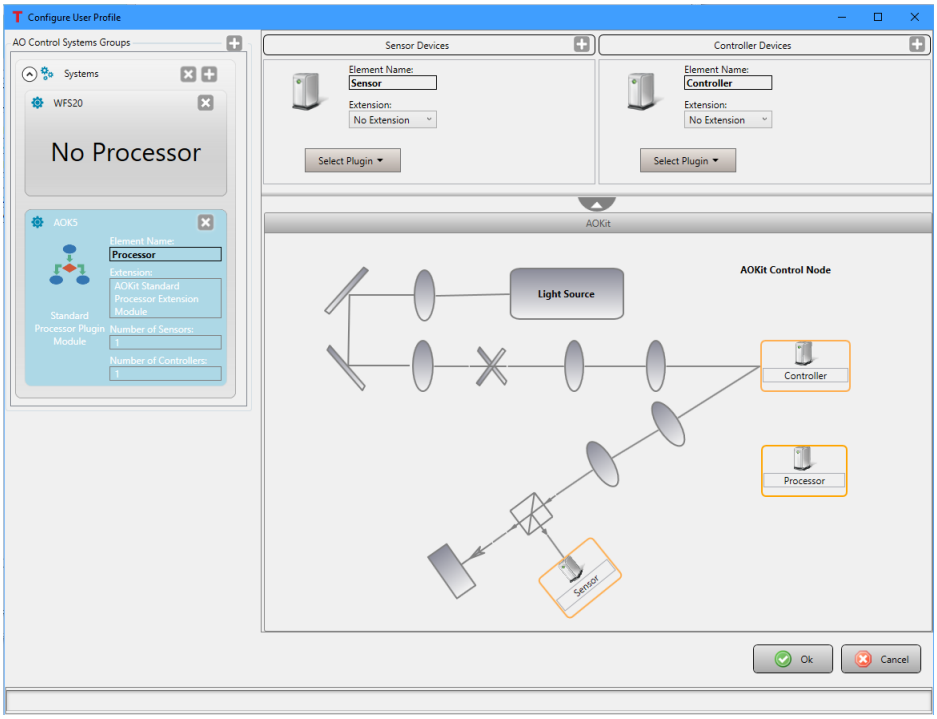


Figure 83 The Configure User Profile Window is showing a newly created system titled AOK5. No sensor or controller has been selected. A conceptual layout is displayed in the lower right of the window, providing a graphical representation of the system.

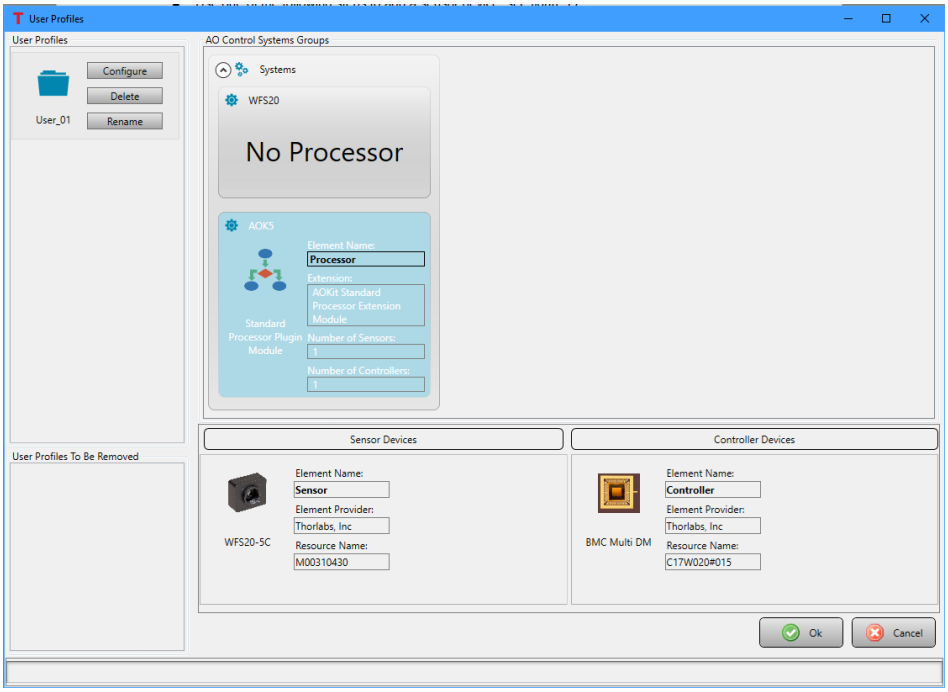


Figure 84 ***The User Profile window is showing a newly created system titled AOK5. With the AOK5 control system highlighted, the details related to the linked devices are displayed under the Sensor Devices and Controller Devices headings.***

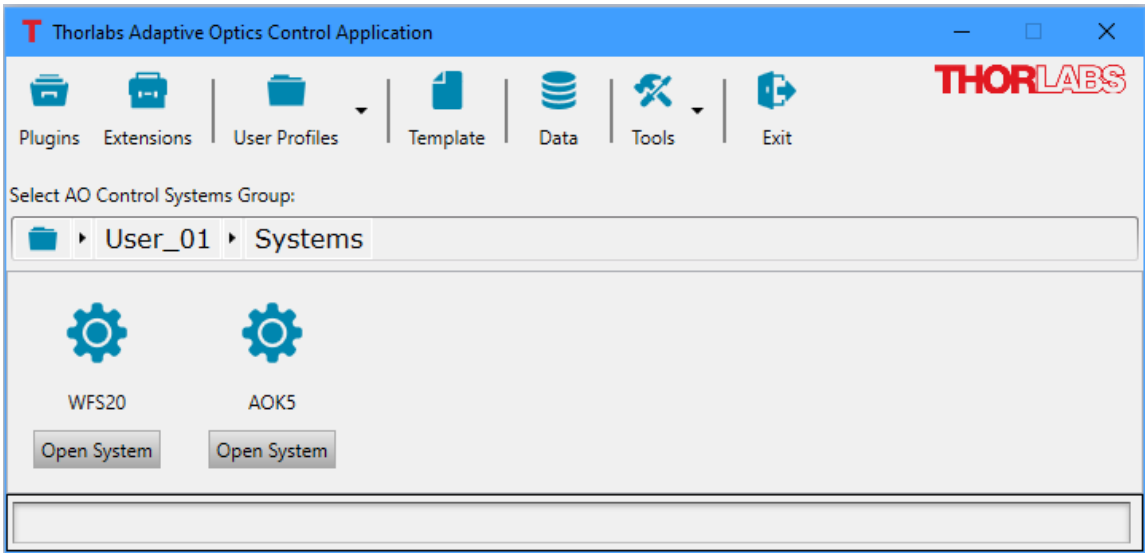


Figure 85 ***The Main control application window is showing a newly created system titled AOK5 within the User Profile User_01 and Control Systems Group Systems.***

7.3. Creating a Woofer-Tweeter-WFS AO Control System

To create a dual-deformable mirror / single wavefront sensor AO control system, also known as woofer-tweeter AO control systems:

1. Add a name for the system into the New Control Group/System window (Figure 76) or the New Control System window (Figure 77).

2. Click the button to the left of the **Create System From Template** option. Then select the template named WooferTweeter. A processor will appear in the Selected Processor box at the right side of the window. See Figure 86. There is a dropdown menu under the Extension option for the processor; from this menu select the processor type to use with the AO control system. Three options are available: AO Kit WooferTweeter Lagrange Based Processor Extension Module, AO Kit WooferTweeter Orthogonal Based Processor Extension Module, and AO Kit WooferTweeter Standard Processor Extension Module. See Section 5.3 for details about these three options.

3. Click the **Ok** button to continue. This will update Configure User Profile window, showing the newly created system. Figure 87 shows the Configure User Profile window, with a newly created system titled AOWT_LagrangeAlgorithm within the Control System Group titled Systems. The AOWT_LagrangeAlgorithm system displayed within the Control Systems Groups section at the left of the window shows the processor extension name (AO Kit WooferTweeter Lagrange Based Processor Extension Module in this example), and the number of sensor and controllers supported by the processor extension is noted. There are no devices linked to the system, evident with no sensor or controller device listed under either category on the right side of the window.

4. Follow step 5 in Section 7.1 to select sensor device.

5. Follow step 6 in Section 7.1 to select controller device for Woofer element. In this example the DMP40 controller modules is selected (Figure 87).

6. Repeat step 5 to select a controller device for Tweeter element. In this example the BMC Multi DM controller module is selected (Figure 88).

7. Click the Ok button to close the window, which will update the User Profile window to include the details about the devices linked to new system. See Figure 89.

8. Clicking the Ok button in the User Profile window will cause the Main window to update. An icon will appear in the lower section of the window when the Control System Group within the User Profile within which the system was created is selected. See Figure 90.

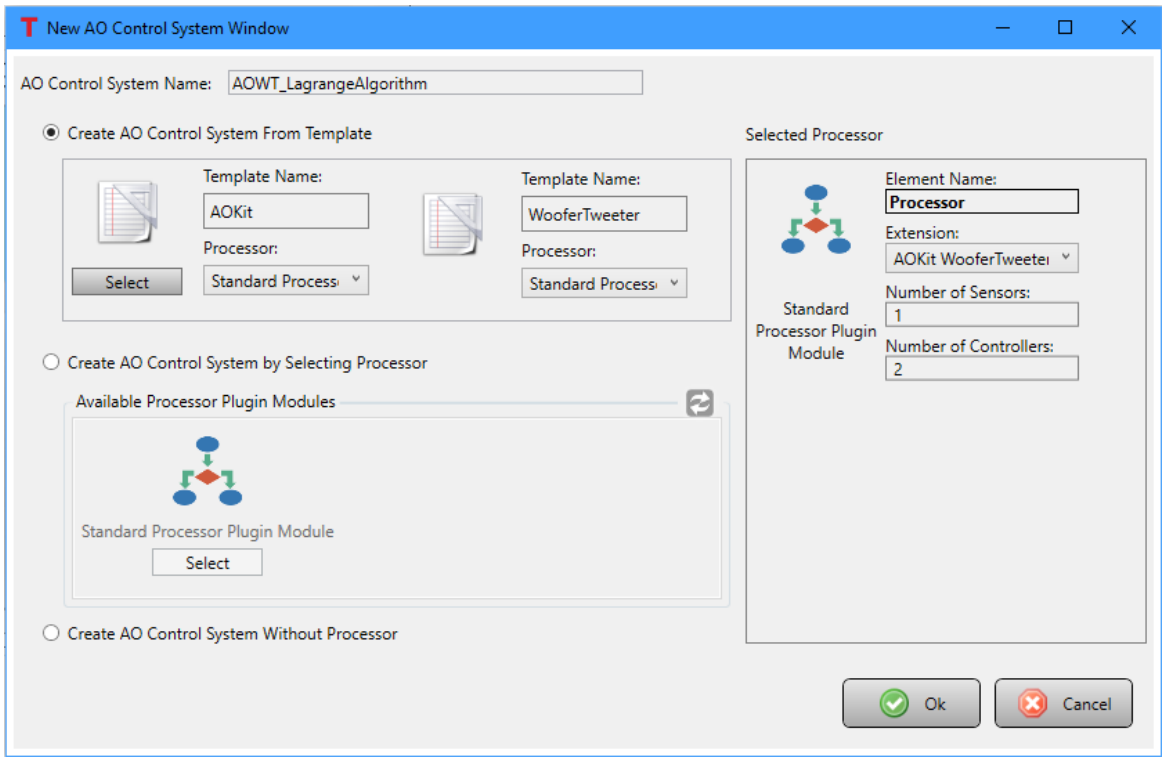


Figure 86 Within the Create Control System From Template options, select the WooferTweeter template.

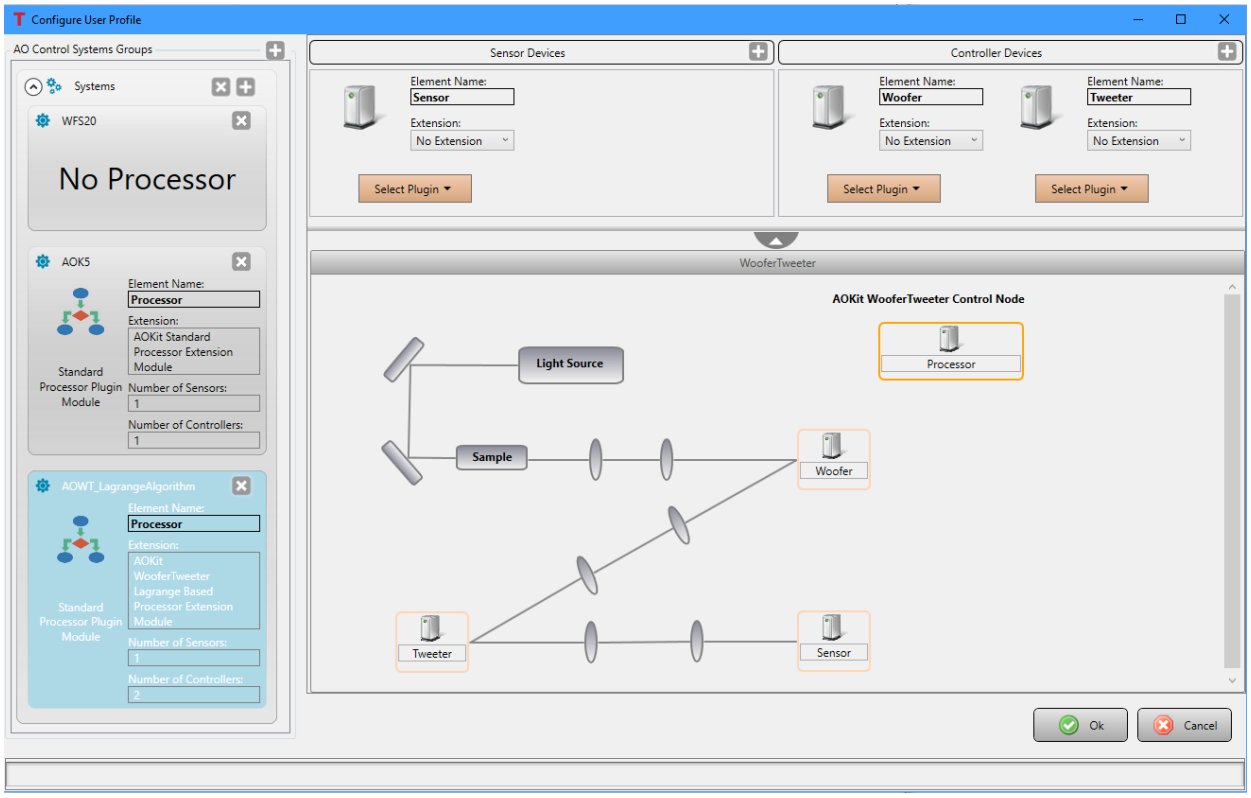


Figure 87 Configure the User Profile window with newly created AOWT_LagrangeAlgorithm; the sensor and controller are not selected.

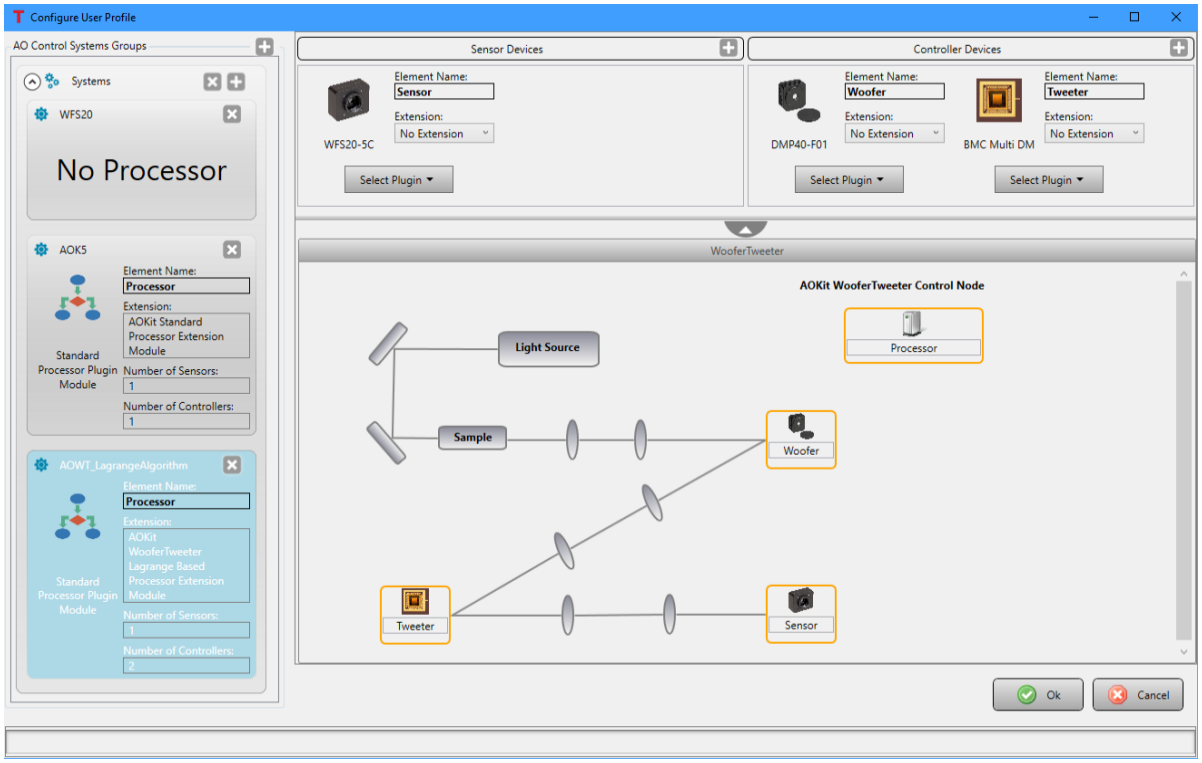


Figure 88 Configure User Profile window with newly created AOWT_LagrangeAlgorithm; the sensor and two controllers are selected.

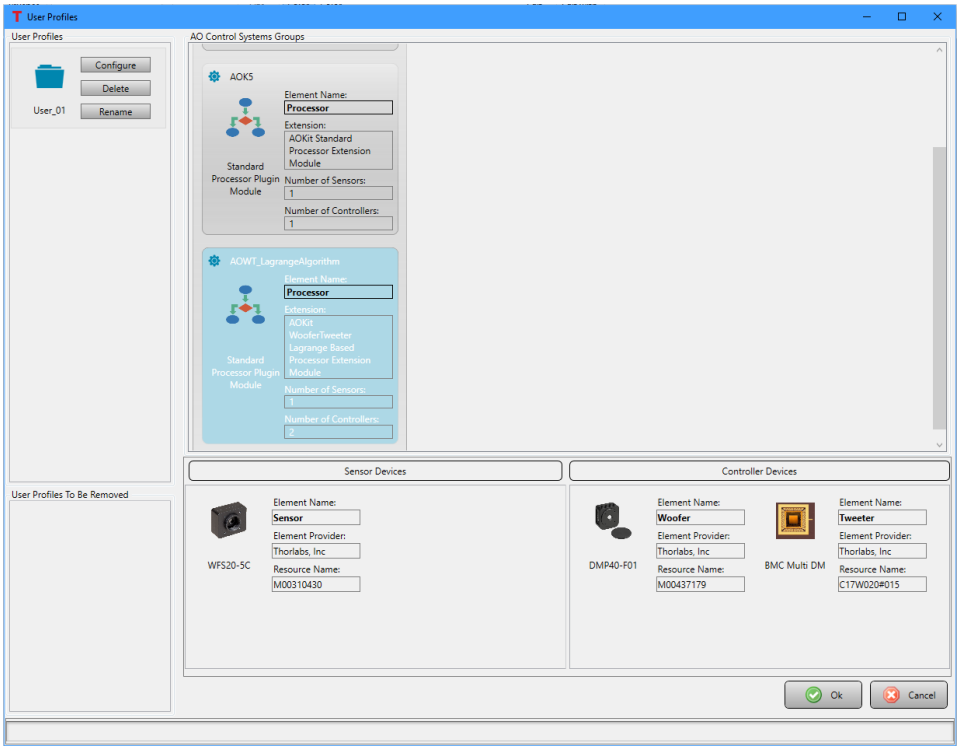


Figure 89 User Profile window is showing the newly created Woofer-Tweeter control system, as well as the details about the linked sensor and controller devices.

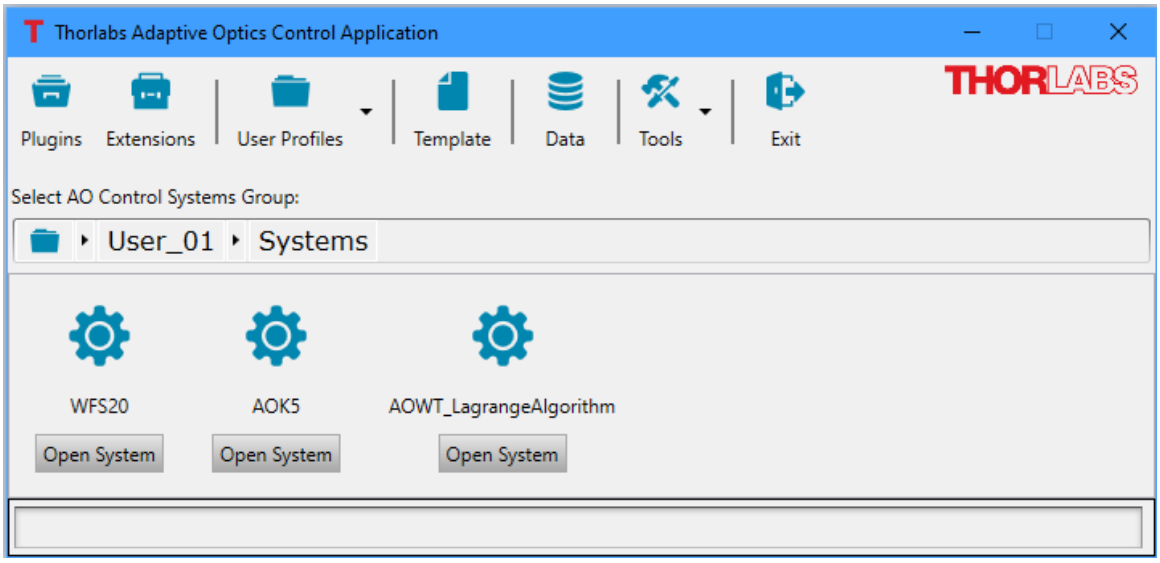


Figure 90 The main Control Application window now shows the newly added AOWT_LagrangeAlgorithm system icon.

Chapter 8 Control System Window

Clicking the **Open System** button under the selected control system icon (⚙) from the main window will bring up a Control System window. The clicked **Open System** button is disabled and overlaid with a running red circular progress bar (for example, see control system AOK5 in Figure 92). Some other **Open System** buttons may be disabled too, if the control system shares the devices with the running control system AOK5. For example, hovering the cursor over control system WFS20, a popup shows **"Device WFS20-5C is used in open control node AOK5"**, as seen in Figure 91.

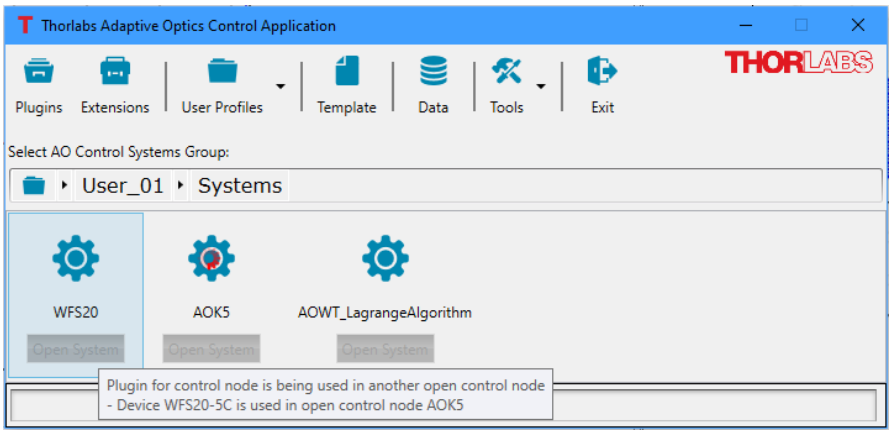


Figure 91 The Main Window Showing a Running Control System

The Control System window contains three (3) sections, which are common to all user defined systems. The specific content will vary between systems. See Figure 92. The three sections are: 1) Toolbar/Controls, 2) Elements parameters and element data display, and 3) Status area.

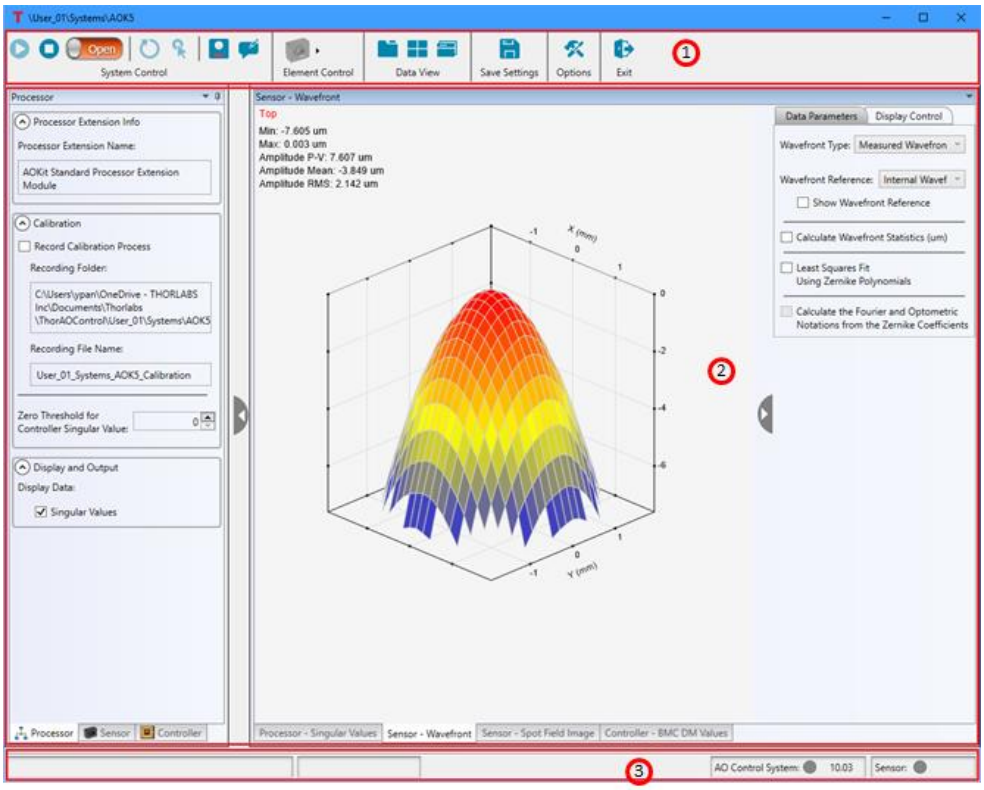
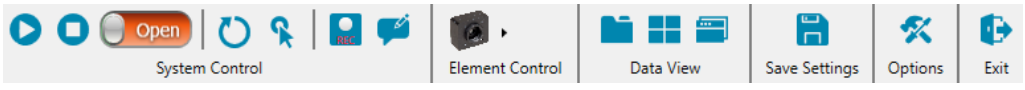


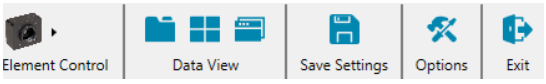
Figure 92 Control System Window Regions
1) Toolbar, 2) Element and Data Display, and 3) Status Area

8.1. Toolbar

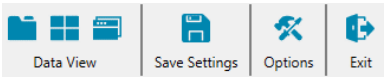
The System Window toolbar will appear different for the various system types: deformable mirror only system, a wavefront sensor only system and a full control system. Figure 93 shows the different toolbars.



(a)



(b)



(c)

Figure 93 Control System Window Toolbars: (a) Full Control System, (b) WFS Only System, and (c) DM Only System

8.1.1. System Control

The **System Control** appears on the Control System window for systems which include processor modules. Table 2 explains the functionality of each of the controls.

System Control Icon	Functionality
 **(1)**	**Run button**: The darker blue button indicates the system is not running. Press it to start collecting WFS data and updating data graphical displays. The faded blue button indicates the system is running.
 **(1)**	**Stop button**: The faded blue button indicates the system is not running. The darker blue button indicates the system is running. Press it to stop collecting WFS data and updating data graphical displays.
 **(1)**	**Loop Control button**: When the button is red with the text Open showing, the system is in open-loop control mode. After calibrating the system, the button may be clicked to put the system into closed-loop control mode. When the button is green with the text Closed showing, the system is in closed-loop control mode. Clicking the button will switch the system in to open-loop control mode.
	**Initialize Control System button**: This button initializes the arrays used by the application to manage data. When the resolution of the wavefront sensor is changed the system arrays must be reinitialized. This button will be faded when the system is running. When the Run, Stop and Loop Control buttons are faded, the system arrays need to be initialized.
	**Calibrate Control System button**: Clicking this button initiates the calibration process defined by the control processor linked to the system when it was set up. This button will be faded when the system is running. To calibrate a system, it must not be running.
	**Record Data button**: Clicking this button will initiate recording data. This button will be faded when the system is not running, and darker when it is running. The recording parameters are set using the Options toolbar icon; see the details in Section 8.1.5.
	**Recording Comment button**: Clicking this button opens a window into which one may enter a comment that will be saved with the data set.

Table 2 Toolbar System Control Icon Functionality
(1) if these 3 buttons are all faded, the system needs to be re-initialized using the Initialize Control System button.

8.1.2. Element Control

The **Element Control** appears on the Control System window for Wavefront Sensor only control systems. When clicked, the Element Control button will display a dropdown menu. See Figure 94. Each of the available dropdown menu items has the same functionality as its corresponding **System Control** toolbar control.

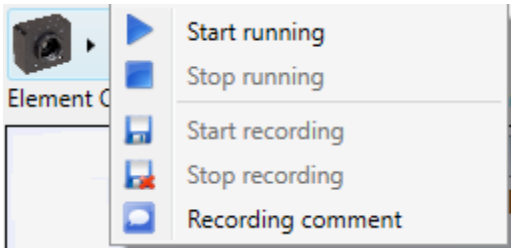


Figure 94 Element Control Button

Element Control Dropdown	Functionality
Start Running	Clicking this button will start collecting WFS data and updating data graphical displays.
Stop Running	Click this button to stop collecting WFS data and updating data graphical displays.
Start Recording	Clicking this button will initiate recording data. The recording parameters are set using the Options toolbar icon; see the details in Section 8.1.5.
Stop Recording	Clicking this button will stop recording data.
Recording Comments	Clicking this button opens a window into which one may enter a comment that will be saved with the data set.

Table 3 Element Control Dropdown Functionality
(1) if these 3 buttons are all faded, the system needs to be re-initialized using the Initialize Control System button.

8.1.3. Data View Controls

The three (3) Data View icons on the toolbar control how the open data windows are displayed. Table 4 details the functionality of these controls.

Data View Icon	Functionality
	Clicking this button will arrange all open data graphical display windows such that each display is its own tabbed page. See Figure 95
	Clicking this button will arrange all open data graphical display windows such that the data windows are arranged in a tiled format. See Figure 96
	Clicking this button will remove the graphical display windows from the control system window. Additionally, each data window will be independent from each other. See Figure 98. Clicking either of the other two buttons will associate the data windows with the control system window and lay them out accordingly.

Table 4 Data View Control Icons

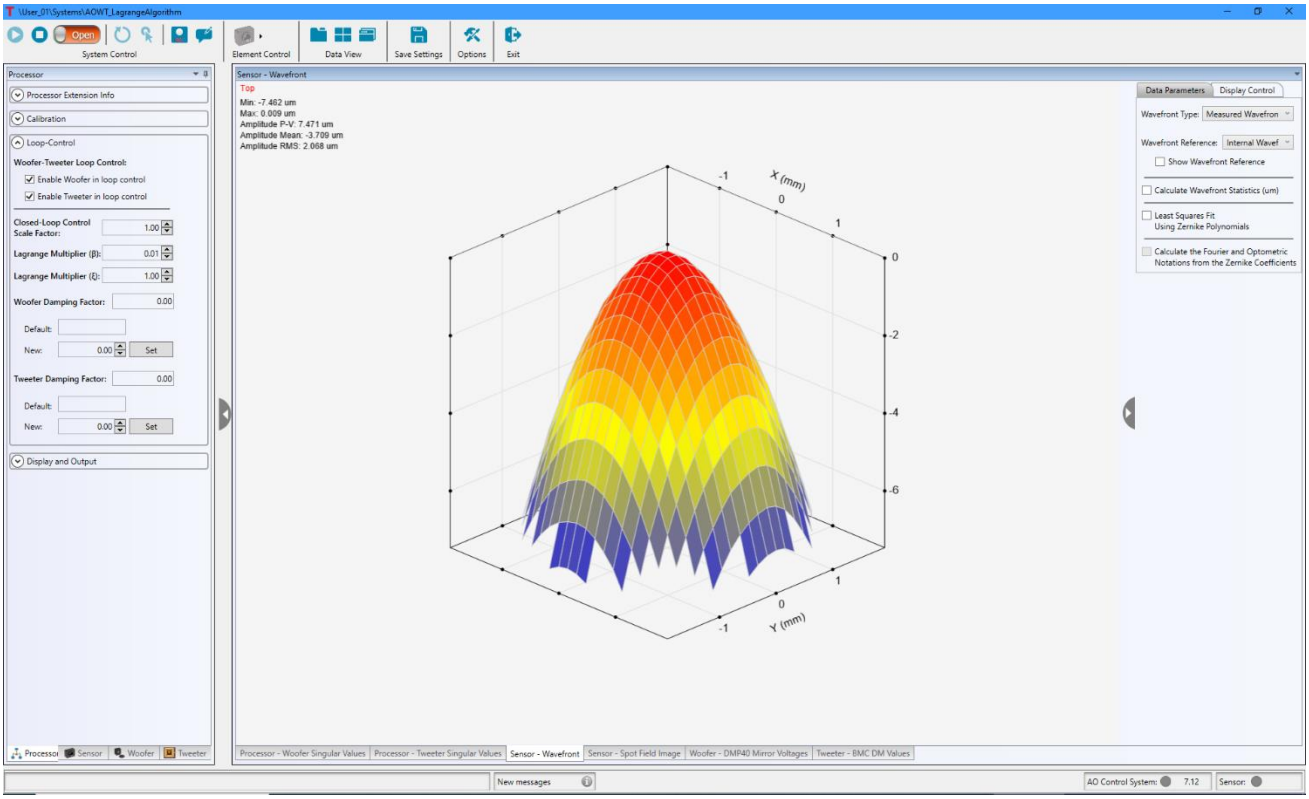


Figure 95 Graphic Data Display Windows Arranged in Tabular Form

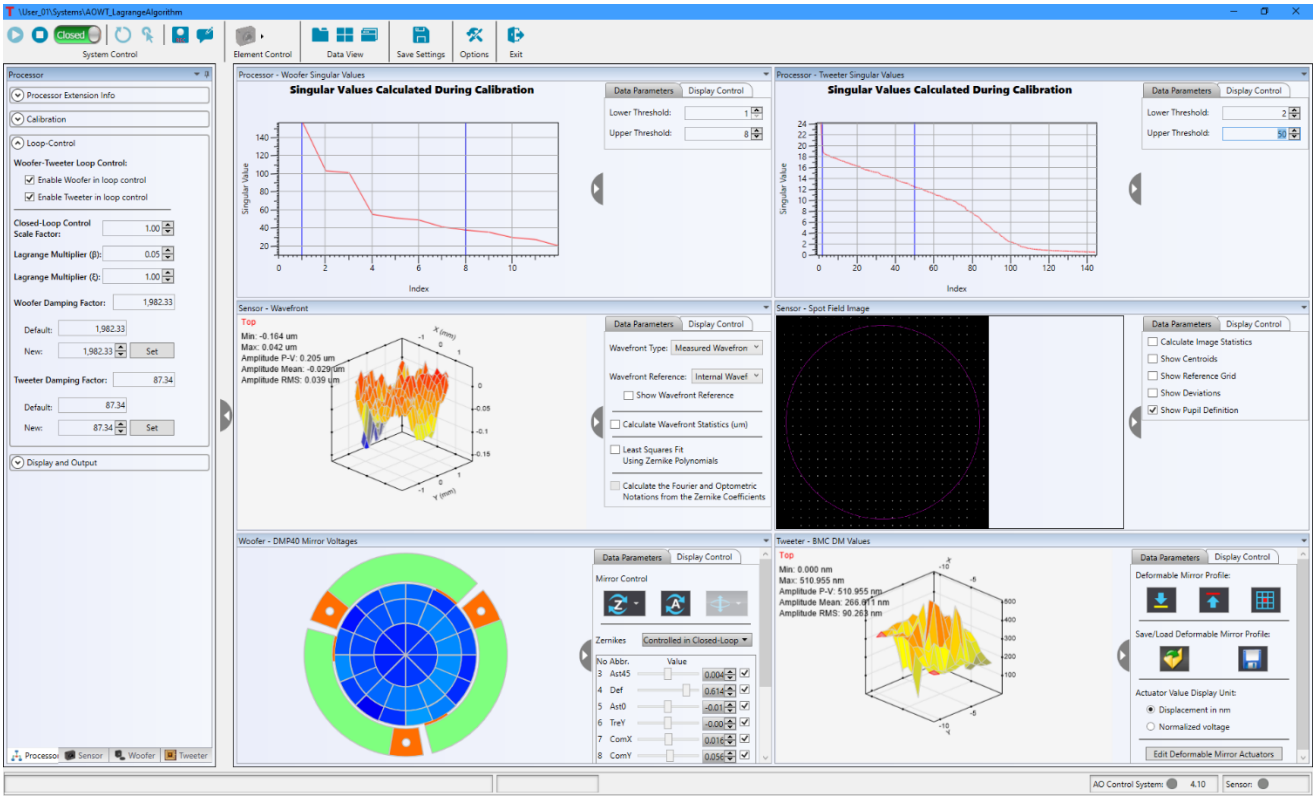


Figure 96 Graphic Data Display Windows Arranged in Tile Form

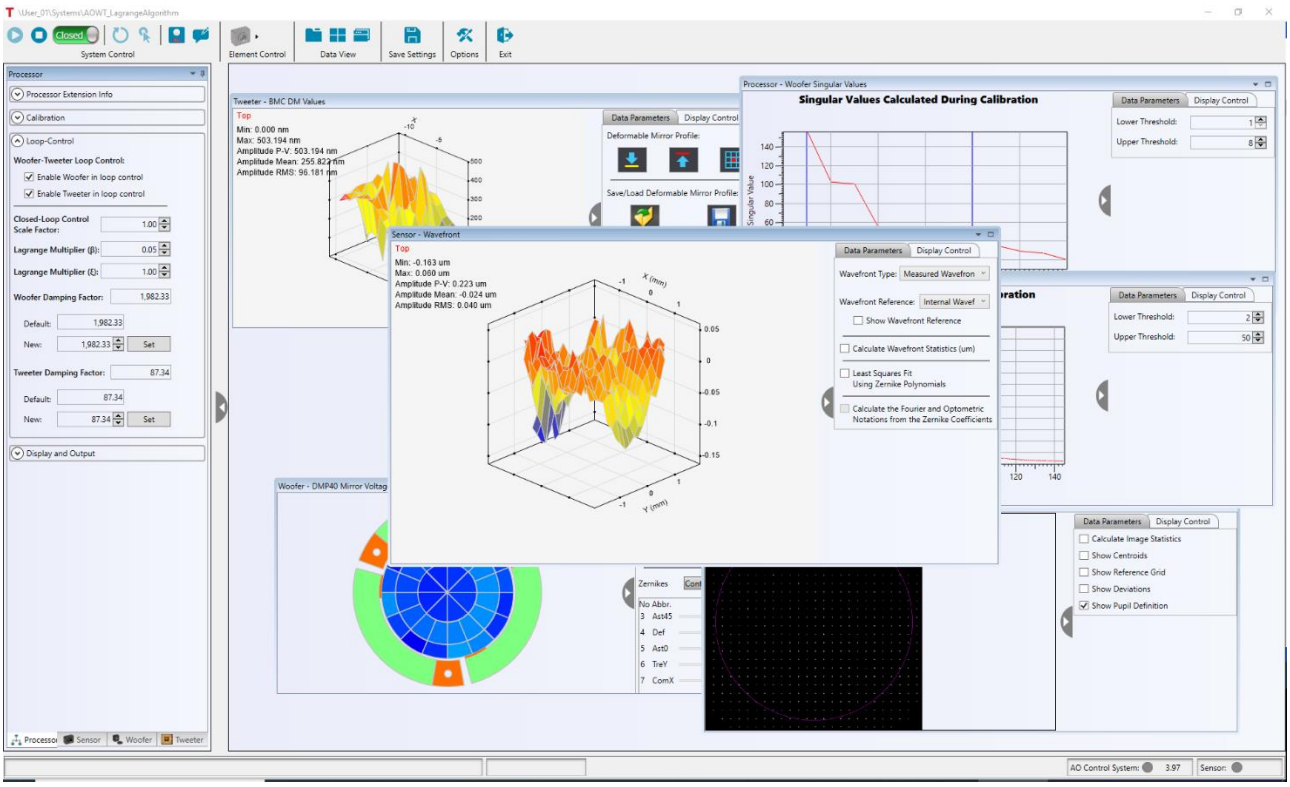


Figure 97 Floating Graphic Data Display Windows

8.1.4. Saving Settings Control

Data View Icon	Functionality
	Clicking this button will save the current settings within the Processor, Sensor and Controller Plugins linked to the System. The plugin setting tabs and the toolbar icon are highlighted with red boxes in Figure 98.

Table 5 Save Settings Button Functionality

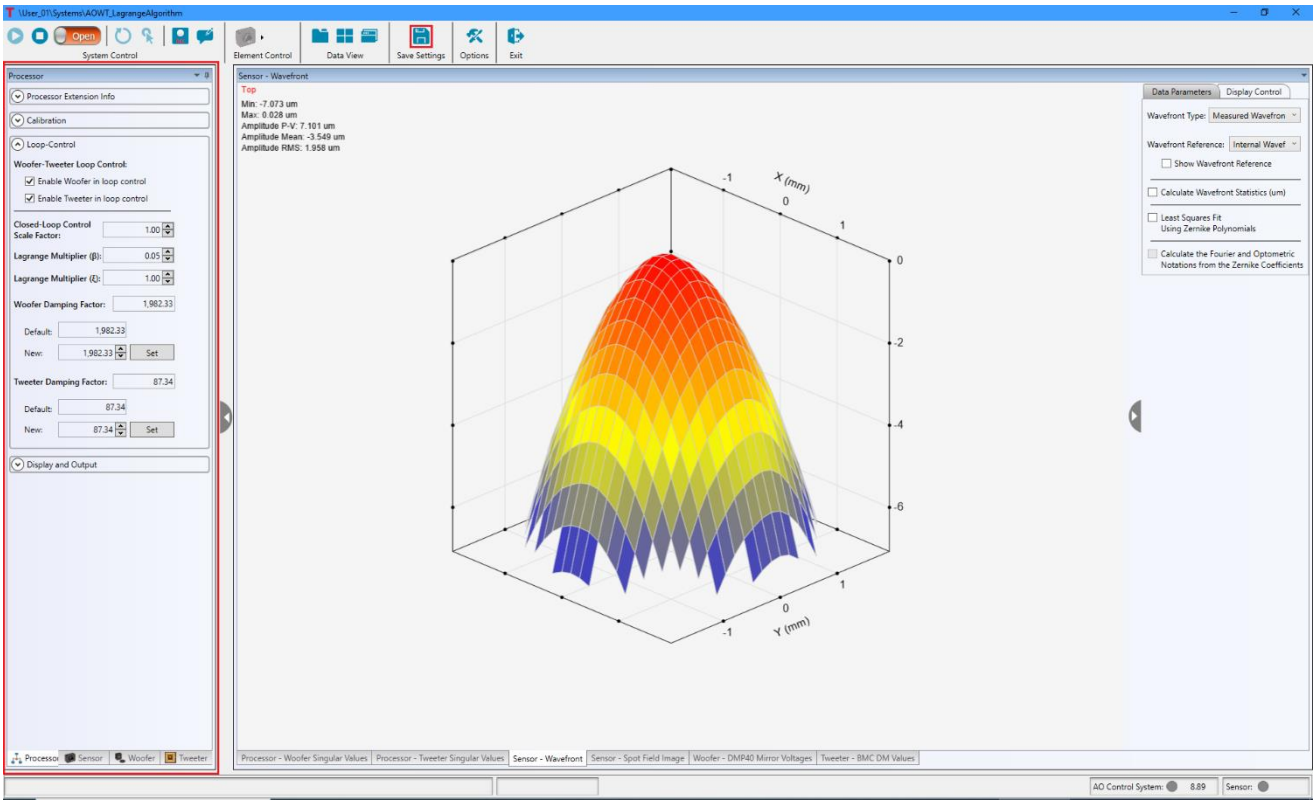
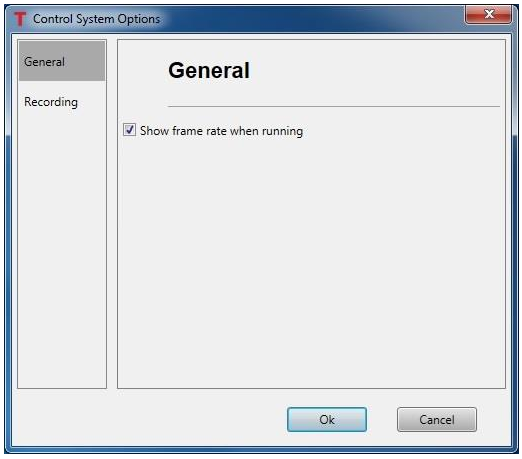


Figure 98 The settings for the processor, sensor and controller plugins (left region highlighted red) are saved using the Save Settings button (icon highlighted in red box on the top toolbar).

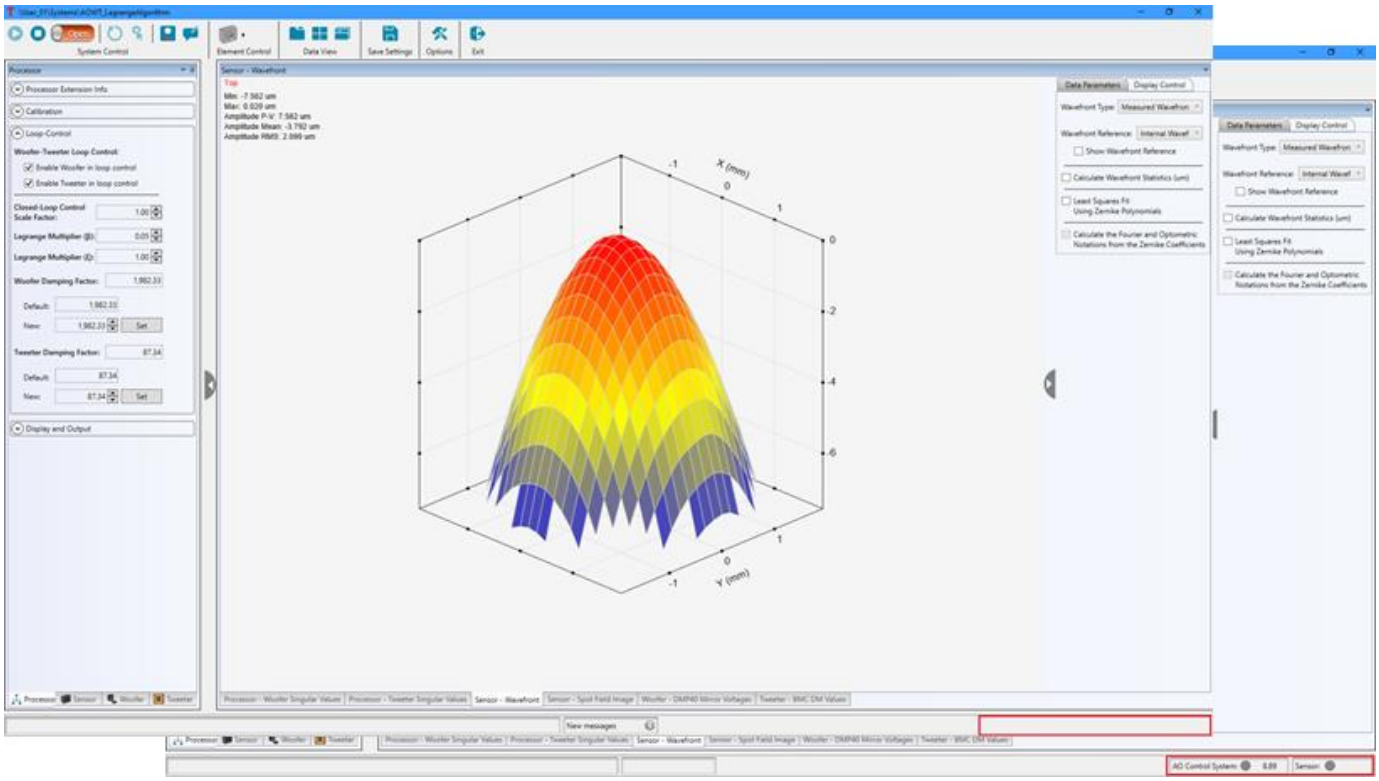
8.1.5. Options Control

Clicking this button will open the Control Systems Options window (Figure 99), which contains general and recording options.

General options – set whether the measurement/control rate is displayed in the lower right corner of the Control System window.



(a)



(b)

Figure 99 The checkbox labeled "*Show frame rate when running*" (a) sets whether the frame rate is displayed in the lower right corner of the System window (b). The top screen capture shows the frame rate absent, while the bottom screen capture shows it displayed.

Recording options – sets the file location, when data collection starts and for how long data will be taken.

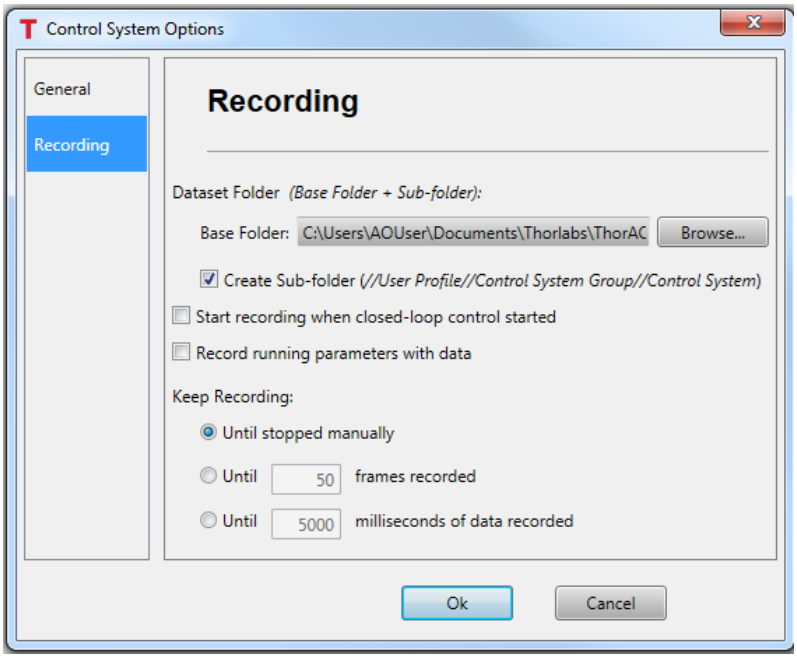


Figure 100 Options for Recording Data

Settings for recording data:

- **Base Folder** - The default location for the datasets is in *C:\Users\<Windows_User_Name>\Documents\Thorlabs\ThorAOControl*

  The location of the data may be selected by clicking the browse button to pop up a window, which will allow one to navigate to the desired folder and save the new location.

- **Create sub-folder *(//User Profile//Control System Group//Control System)*** - With this box unchecked the data file is saved in the folder defined by the base folder. When it is checked, the following path is appended to the defined Dataset Folder:

  \<User_Profile>\<Control_System_Group_Name>\<Control_System_Name>

  An example would be
  C:\Users\AOUser\Documents\Thorlabs\ThorAOControl\User_01\Systems\AOWT_LagrangeAlgorithm

- **Start recording when closed-loop control started** - Checking this box sets it such that the data recording starts when the closed-loop control is activated.

- **Record running parameters with data** - If this box is checked, when data is recorded, additional xml files will be written to the file, with each file containing the settings for the various plugin modules at time the data was recorded. These could include the settings for the control processor, the sensor element and the controller element.

  The following details the files saved for various system types.

  1. Sensor Only system

     a. <system_name>_<4-digit number>_Sensor_Parameters.xml

2. Controller only system:
    a. Not applicable.
3. Single DM / single WFS system:
    a. <system_name>_<4-digit number>_Processor_Parameters.xml
    b. <system_name>_<4-digit number>_Sensor_Parameters.xml
    c. <system_name>_<4-digit number>_Controller_Parameters.xml
4. Two DM / single WFS system:
    a. <system_name>_<4-digit number>_Processor_Parameters.xml
    b. <system_name>_<4-digit number>_Sensor_Parameters.xml
    c. <system_name>_<4-digit number>_Woofer_Parameters.xml
    d. <system_name>_<4-digit number>_Tweeter_Parameters.xml

- **Keep Recording** - There are three (3) options for how long data recording will continue:
    - **Until stopped manually** - Continue recording data until the **Start Recording Data/Stop Record Data** button () is pressed.
    - **Until a user defined number of frames recorded** - Continue recording data until a user defined set of data frames (sets) are recorded.
    - **Until a user defined number of milliseconds of data recorded** - Continue record data until a user defined time in milliseconds has transpired.

8.1.6. Exit Control

Clicking this button will shut down all running processes and close the control system window. All the running parameters will be saved into the configuration files within the Processor, Sensor and Controller Plugins linked to the System.

8.2. Elements

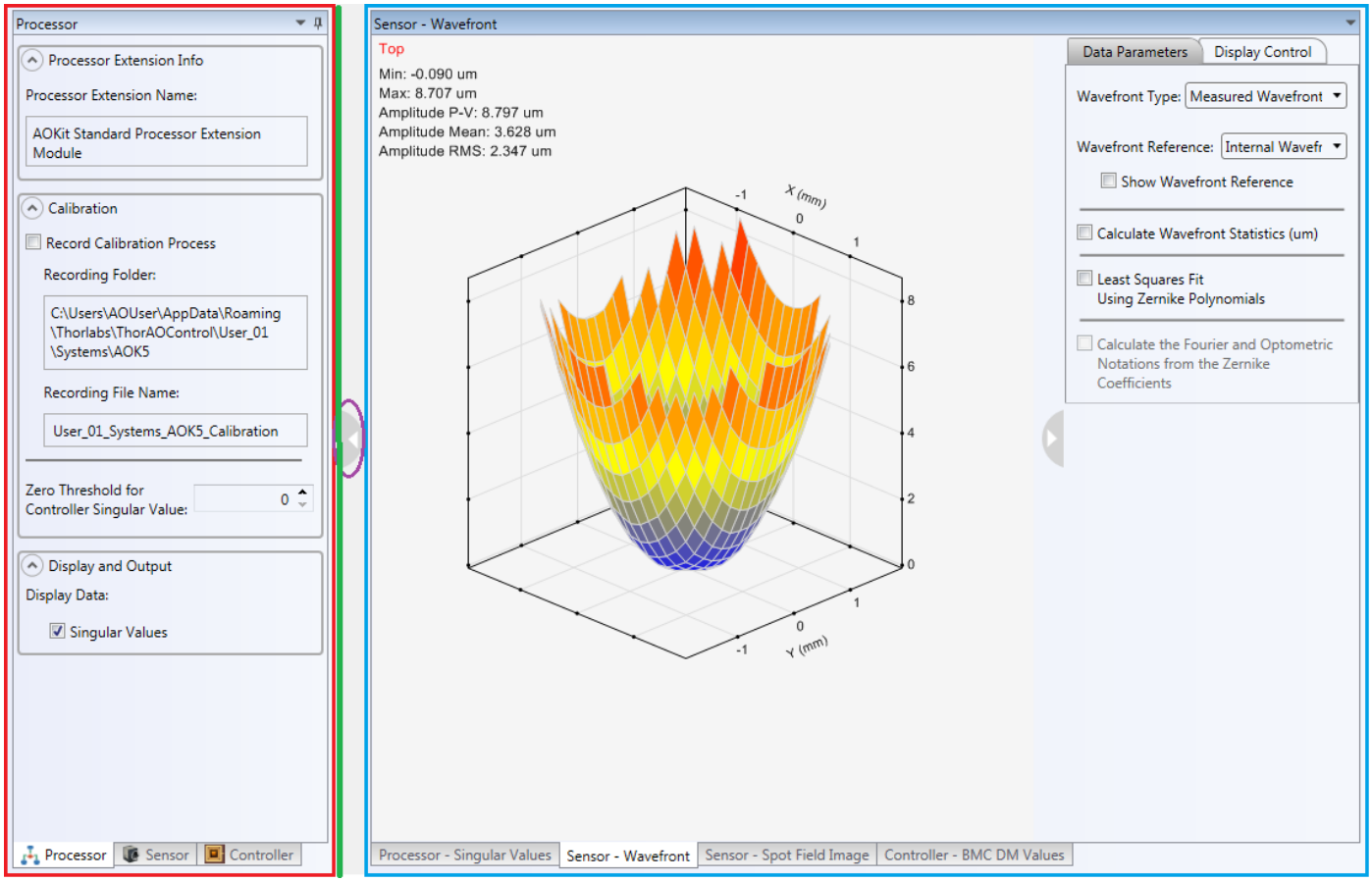


Figure 101 Element Parameters Tabular Control and Data Display Panel

In the middle left of the control system window, as shown in Figure 101, a tabular control (red box) holds tab pages for each element linked to the system. Each tab page includes the information and running parameters for the element. The specific elements and tab contents may vary depending on the system. The element parameters are set to default values when the control system is initially run. It is highly recommended that all settings be reviewed and adjusted to suit the application.

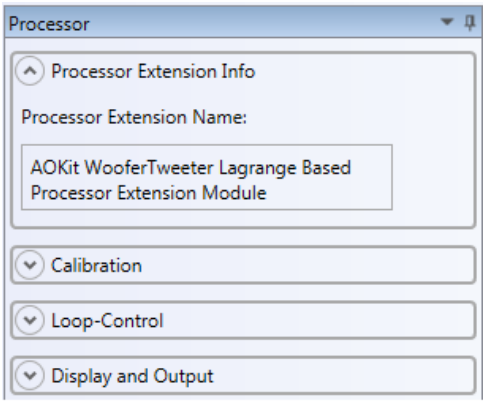
A panel (blue box) holds the windows to display the data and the parameters associated to the data control and the display control. These windows could be arranged in tabbed pages, tile form or as floating windows, see Section 8.1.2.

A green line represents the splitter between the element parameters tabular control and data display panel. Hovering the cursor over the green line will change the cursor to ⇦⇨ and allow user to resize the tabular control or data display panel horizontally. Alternatively, the element parameter tabular control may be collapsed by clicking the grey semi-circle at the right edge of the tab display (purple oval).

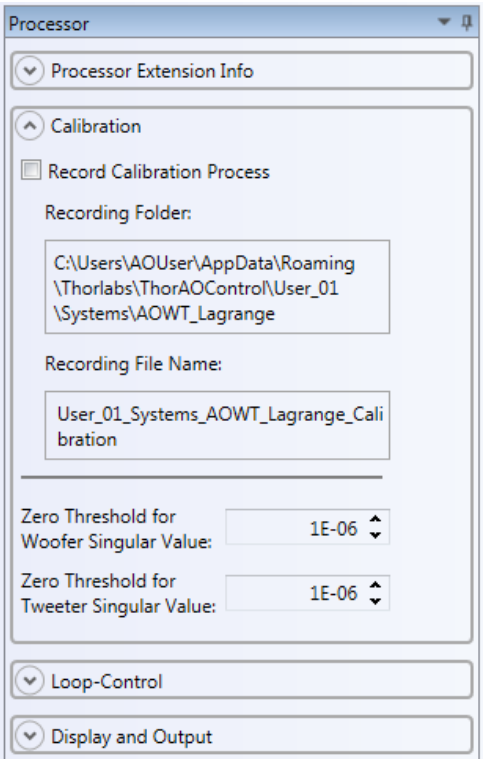
8.2.1. Processor Element – Standard Processor

8.2.1.1. Processor Element Parameters Tab

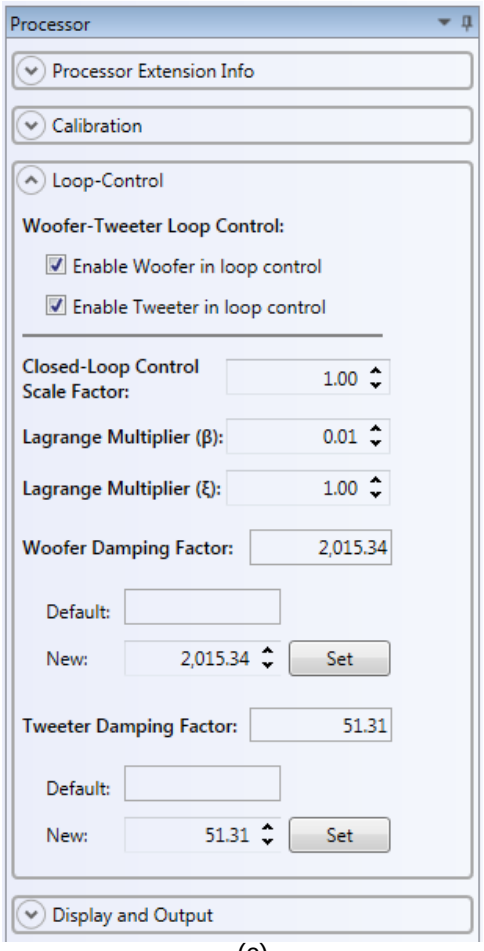
The contents of the processor element tab vary depending on the loaded processor extension. Typically, a processor element tab has four sections: **Processor Extension Info**, **Calibration**, **Loop-Control**, **Display and Output**. Figure 102 shows the processor tab for AOKit_WooferTweeter_LagrangeBased Extension.



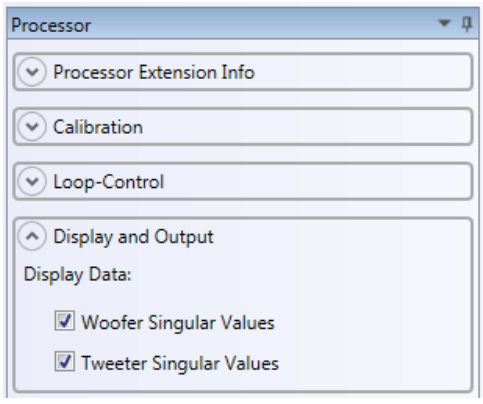
(a)



(b)



(c)



(d)

Figure 102 AOKit_WooferTweeter_LagrangeBased Processor Tab

(a) Processor Extension Info, (b) Calibration, (c) Loop-Control, (d) Display and Output

Processor Extension Info: This section displays the full extension name.

Calibration: This section includes a checkbox that if checked allows measurements made during the calibration process to be stored in the noted folder path and file name. Additionally, the zero threshold used for calculating the controller singular value using Singular Value Decomposition (SVD) may be set here.

Display and Data Output: This section includes check boxes that set the display state of the controller singular value plot windows.

Loop-Control: This section provides user changeable settings for AO Kit closed-loop control. The parameters vary depending on the loaded processor extension:

- **Woofer-Tweeter Loop Control** – Applied to all types of Woofer-Tweeter extensions. Two checkboxes at the top of the Loop Control section allow a user to enable/disable updating of the woofer and tweeter control signal values.

- **Closed-Loop Control Scale Factor (g)** – Only applied to AOKit_WooferTweeter_LagrangeBased Extension, see definition in Eq.2 in 5.3.3. This is a gain factor applied to the Woofer and Tweeter control signal values in closed-loop control.

- **Lagrange Multiplier (β)** and **Lagrange Multiplier (ξ)** – Only applied to AOKit_Woofer_Tweeter_LagrangeBased Extension, see definitions in Eq.2 in 5.3.3. These are the weighting factors between the two deformable mirrors to balance the influence of the mirrors.

- **Woofer Damping Factor (λ_1)** and **Tweeter Damping Factor (λ_2)** – Only applied to AOKit_Woofer_Tweeter_LagrangeBased Extension, see definitions in Eq.2 in 5.3.3. The default damping factor values are calculated and set during the calibration process. The starting damping factor for the woofer is the median eigenvalue of $\boldsymbol{A^T A}$, where $\boldsymbol{A}$ is the woofer influence matrix. The starting damping factor for the tweeter is the median eigenvalue of $\boldsymbol{B^T B}$, where $\boldsymbol{B}$ is the tweeter influence matrix. New values can be set in the numeric control labeled **New** and applied to the closed-loop control by clicking button **Set**.

8.2.1.2. Processor Element Data Display

Except AO Kit DMP40 Processor Extension, all other processor extensions have window(s) to display the singular values calculated during the calibration process, as shown in Figure 103.

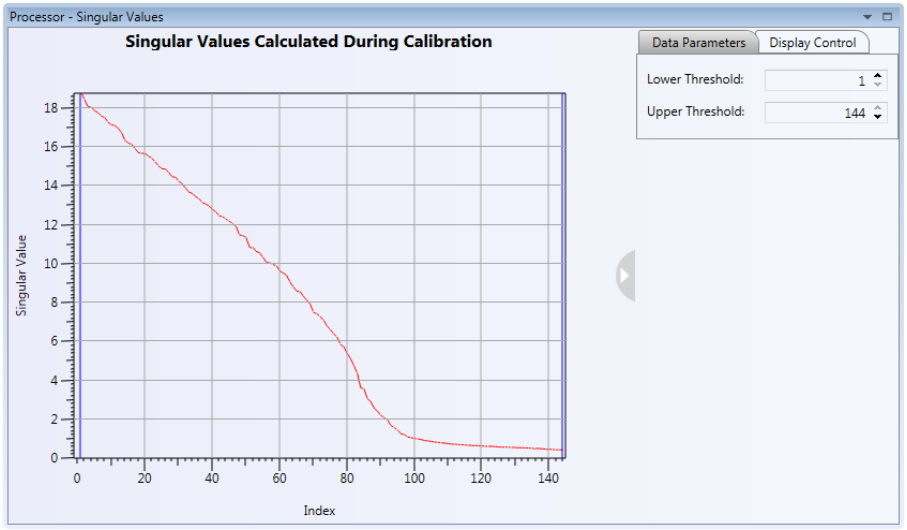


Figure 103 Measured Singular Values Window

Data Parameter Tab

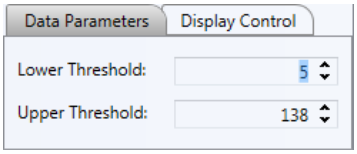


Figure 104 Singular Values Window Data Parameter Tab

The singular values are displayed in a descending order. The user may select a band of mirror eigenmodes to use during closed-loop control by adjusting **Lower Threshold** and **Upper Threshold** values for each mirror. The singular values below the lower threshold and above the upper threshold are set to zeros. Then, using the modified singular values the modified influence matrices are recalculated. The eigenmodes associated with each singular value are subsequently 'disabled' in the system control matrix. Adjusting these values can greatly impact the performance of a system and the user should include adjustments to the ranges in optimizing a system. To start, for a BMC mirror try setting the Lower Threshold to 2 and the Upper Threshold to 55 and for the DMH/DMP start with a Lower Threshold of 1 and the Upper Threshold of 8.

Display Control Tab

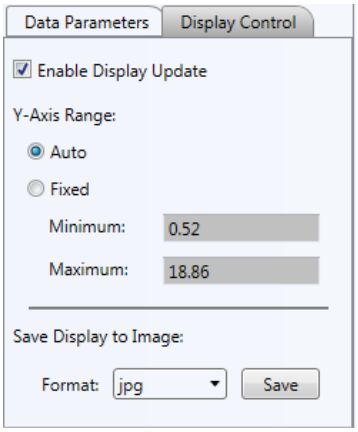


Figure 105 Singular Values Window Display Control Tab

Enable Display Update: Checking this box activates the data to update continuously. Unchecked, it reduces MS Windows resources used to for graphic updates.

Y-Axis Range:

- **Auto**: Selecting this option allows the y-axis range to auto scale.
- **Fixed**: This option allows the y-axis minimum and maximum values to be set manually.

Save Display to Image: The graphical image may be saved. There are four image formats available: jpg, bmp, tif, or png. Clicking the **Save** button will display a standard MS Windows save file dialog box, in which one may navigate to the folder to save the image.

8.2.2. Sensor Element – Thorlabs Wavefront Sensor

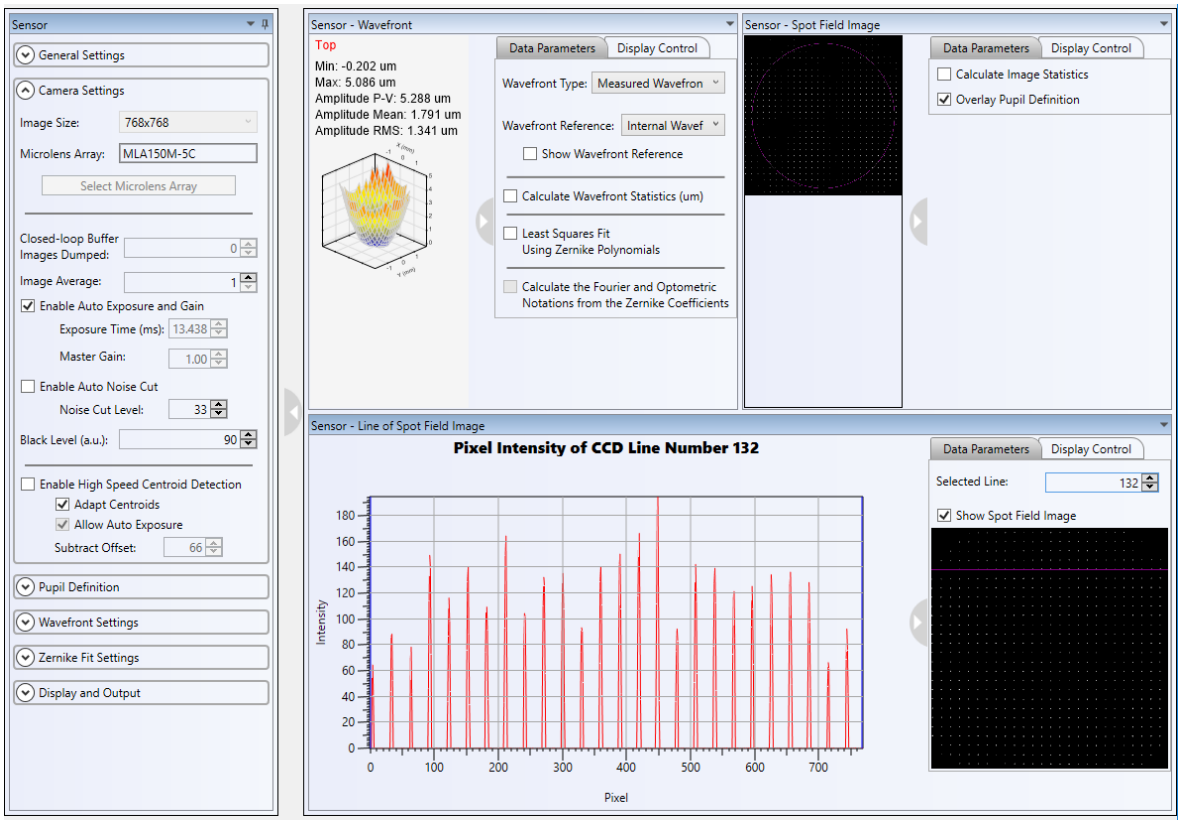


Figure 106 Thorlabs Wavefront Sensor Element Tab and Graphics Data Panel

8.2.2.1. Thorlabs Wavefront Sensor Element Parameters Tab

The Thorlabs WFS plugin includes various settings for the WFS camera, the display of data, data calculation, and outputting data to a file. The settings are grouped into six categories: General Settings, Camera Settings, Pupil Definition, Wavefront Settings, Zernike Fit Settings, and Display and Output. Each group will be detailed below.

General Settings

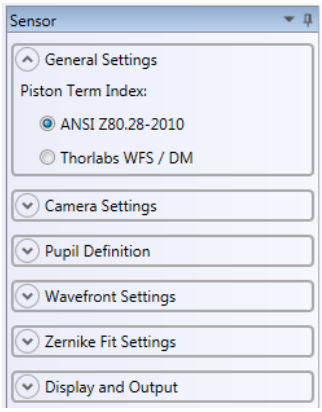


Figure 107 WFS Settings Window – General Settings

Piston Term Index – Defines the Zernike monomials order. Two options: ANSI Z80.28-2010 or Thorlabs' definition used in WFS and DM.

Camera Settings

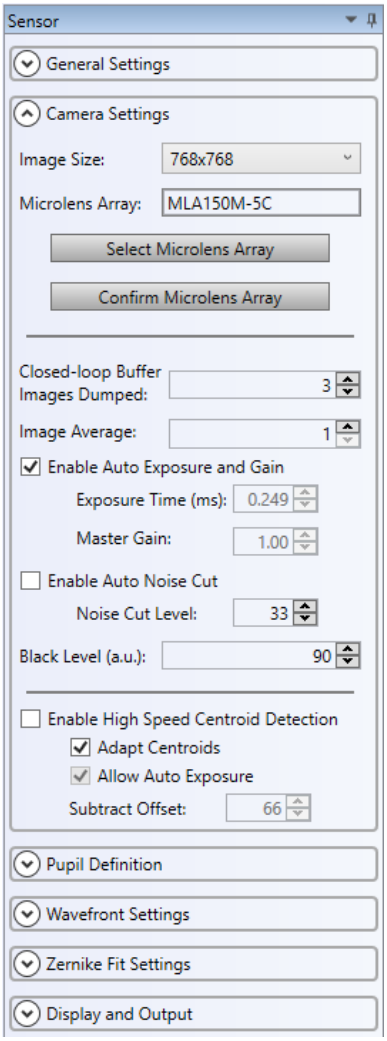
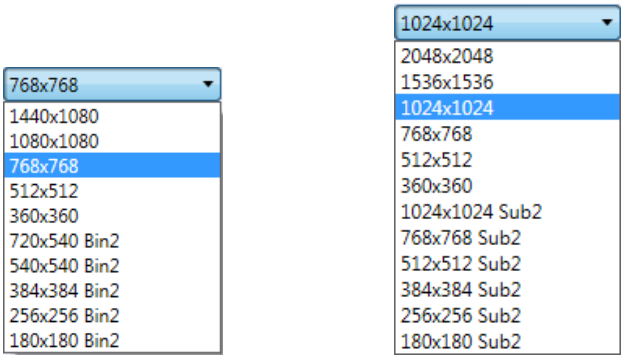


Figure 108 WFS Settings Window – Camera Settings

Image Size – Defines the active area of the camera that is used for wavefront measurement. Large image sizes allow the chosen pupil diameter to be large, which supports a high Zernike resolution (Zernike order). Small image sizes increase the measurement speed while decreasing the maximum achievable Zernike order.



(a) (b)

Figure 109 (a) WFS20 & (b) WFS40 Available Camera Image Sizes

The WFS20 instrument offers a binning mode ("bin2"). In this mode, four pixels in a 2x2 grid are combined and averaged to yield one data point. The result is an increased frame rate with the trade-off of reduced spatial wavefront resolution.

Similarly, the WFS40 offer a "sub2" mode, in which subsampling selects a single pixel out of a 2x2 grid to use for measurement. The measurement speed increases, with the disadvantage of a lower spatial wavefront resolution and accuracy.

Note: Changing the camera resolution will also change the number of detectable spots. If the instrument is operated in an AO control system, a new calibration is required.

Microlens Array – The mounted holder with a Microlens Array (MLA), installed on a Thorlabs Wavefront Sensor, can be exchanged. Each MLA is factory calibrated with the individual Wavefront Sensor. The calibration data are saved to the WFS internal non-volatile memory. In order to supply the correct calibration data to the WFS software, you need to select the physically installed MLA from the pull-down list popped up by clicking **Select Microlens Array** button, and then click **Confirm Microlens Array** button to confirm the selection.

Closed-loop Buffer Images Dumped – During the closed-loop control, the WFS is continuously acquiring the data into its internal buffer while the deformable mirrors are moving to the new position. If the WFS data are acquired during the deformable mirror transition to the new position and are used in the calculation of the controller signal that might cause the closed-loop control failure. To eliminate this error, the specific number of buffered images are dumped before an image is returned and used in the closed-loop control.

Image Average – This will increase the accuracy of detected spot centroids.

Enable Auto Exposure and Gain – If checked, the WFS software automatically set the **Exposure Time** and **Master Gain**. It is recommended that this setting be checked for normal operation. For calibration and closed-loop control, this setting may be unchecked.

- **Exposure Time** – Range depends on the instrument.
- **Master Gain** – Amplification factor of the sensor signal.

It is recommended to change the **Exposure time** to adjust the brightness. Increase the **Master Gain** would also increase the image noise.

Enable Auto Noise Cut – Enables dynamic adaption to the different intensity levels for each spot area and yields the best results for centroid calculation.

- **Noise Cut Level** – Sets the brightness level which a spot intensity must exceed to be included in the data analysis. The value is between 0 and 255.

Black Level – Adjusts the brightness level offset for all illuminated pixels. The value is between 0 and 255.

Enable Hardware Trigger – This setting is currently disabled for AO Control Application.

Enable High Speed Centroid Detection – WFS20 only. If checked, the spot centroid coordinates are calculated inside camera control box. Only the calculated centroid positions are transmitted via USB to the GUI, the spot field image captured inside the camera won't be transmitted via USB. Due to the much lower transmitted data volume, the maximum measurement rate increases.

- **Adapt Centroids** – This parameter determines if the centroid positions measured in normal mode should be used to adapt the spot search windows for Highspeed Mode. Otherwise, a rigid grid based on reference spot positions is used in Highspeed Mode.

- **Allow Auto Exposure** – This parameter determines if the camera should also calculate the image saturation in order to enable the auto exposure feature.

- **Subtract Offset** – This parameter defines an offset level for High-speed Mode only. All camera pixels will be subtracted by this level before the centroids are being calculated, which increases accuracy. The value range is between 0 and 255.

Pupil Definition

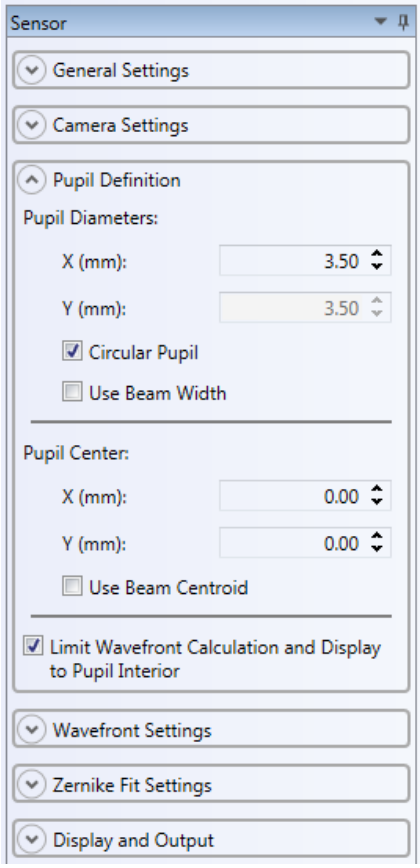


Figure 110 WFS Settings Window – Pupil Definition

Pupil Diameters – The pupil diameters in mm can be set manually or automatically. When **Circular Pupil** is checked, adjusting either the x or y diameter setting will adjust the other setting to keep the pupil circular. If **User Beam Width** is enabled, the pupil diameter is automatically adapted to the measured beam width.

Pupil Center – Changes the center location of the pupil to a specified (x, y) position. It can be set manually or automatically. Enabling **User Beam Centroid** will adapt the pupil center to the measured beam centroid coordinates.

Limit Wavefront Calculation and Display to Pupil Interior – If checked, the wavefront calculation and display will only be limited to the pupil interior.

Wavefront Settings

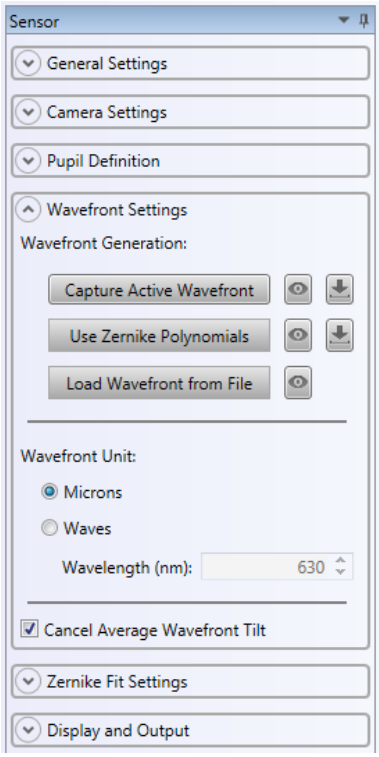


Figure 111 WFS Settings Window – Wavefront Settings

Wavefront Generation – The wavefront generator options provide an easy means of setting a user-defined reference wavefront. It offers three means to achieve this.

- **Capture Active Wavefront** – Allow the user to capture the 'current' active wavefront at the WFS.
- **User Zernike Polynomials** – Click this button will open a separate window that allows one to define a Zernike-based reference wavefront by varying the amount of the various Zernike terms. Figure 111 is an example of the window. The variable Zernike terms are listed at the right side of the screen.

  The first three columns in the Zernike table include the monomial ***index***, ***n*** is the non-negative radial integer index and ***m*** is the meridional signed integer index. The fourth column notes the standard ***Mode Name*** and the fifth column includes numeric controls for adding Zernike components.

- **Load Wavefront from File** – Click this button will open a standard MS Windows control to open a saved reference file. The user may select the location in which the file was saved. The file extension will be *.ref.
- **Button** (👁) – Click this button to display the wavefront generated from one of the three means mentioned above in a separate window. See Figure 112.
- **Button** (⬇) will open a standard MS Windows control to save the file. The user may select the location in which to save the file. The file extension will be *.ref.

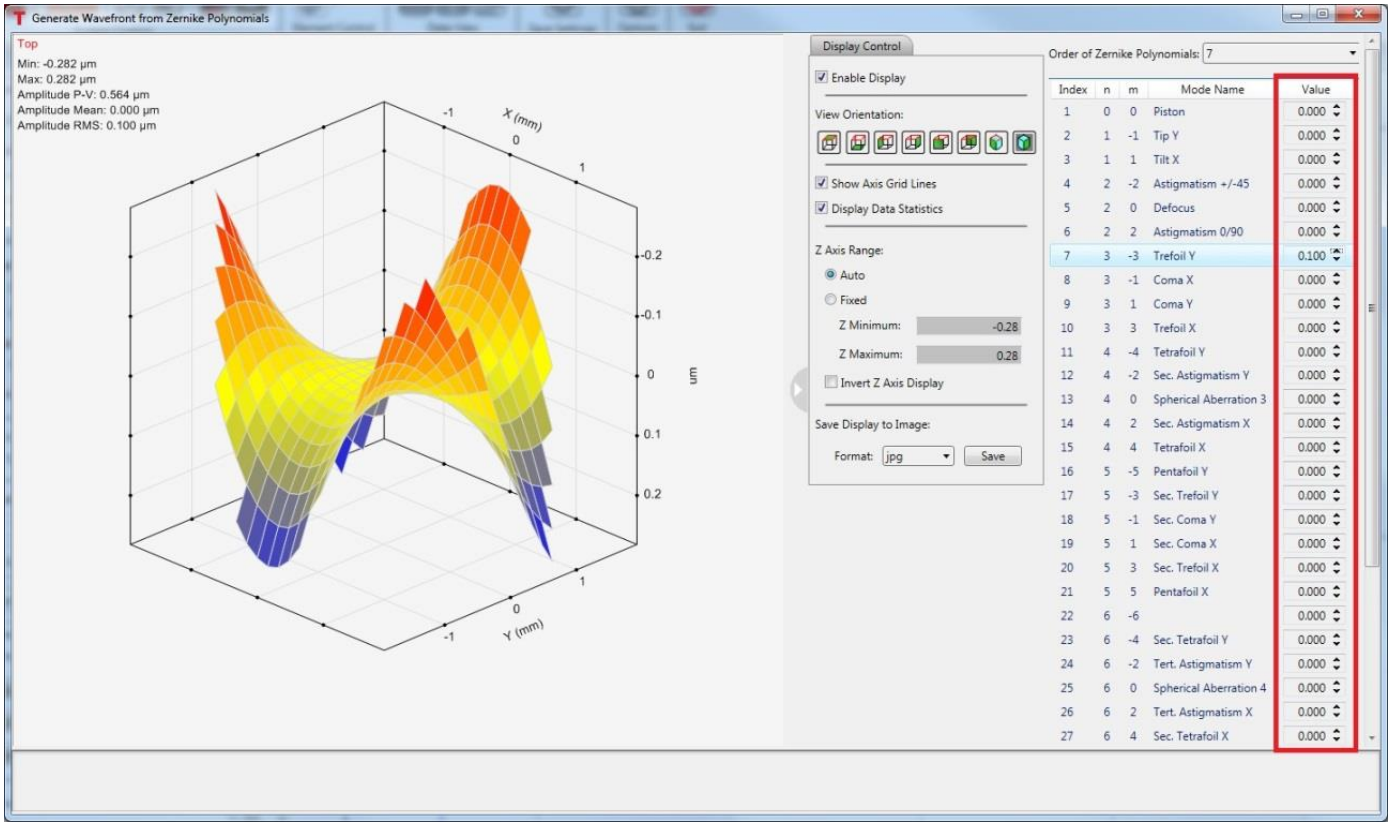


Figure 112 Wavefront Settings Window – Zernike Reference Wavefront Generator Window

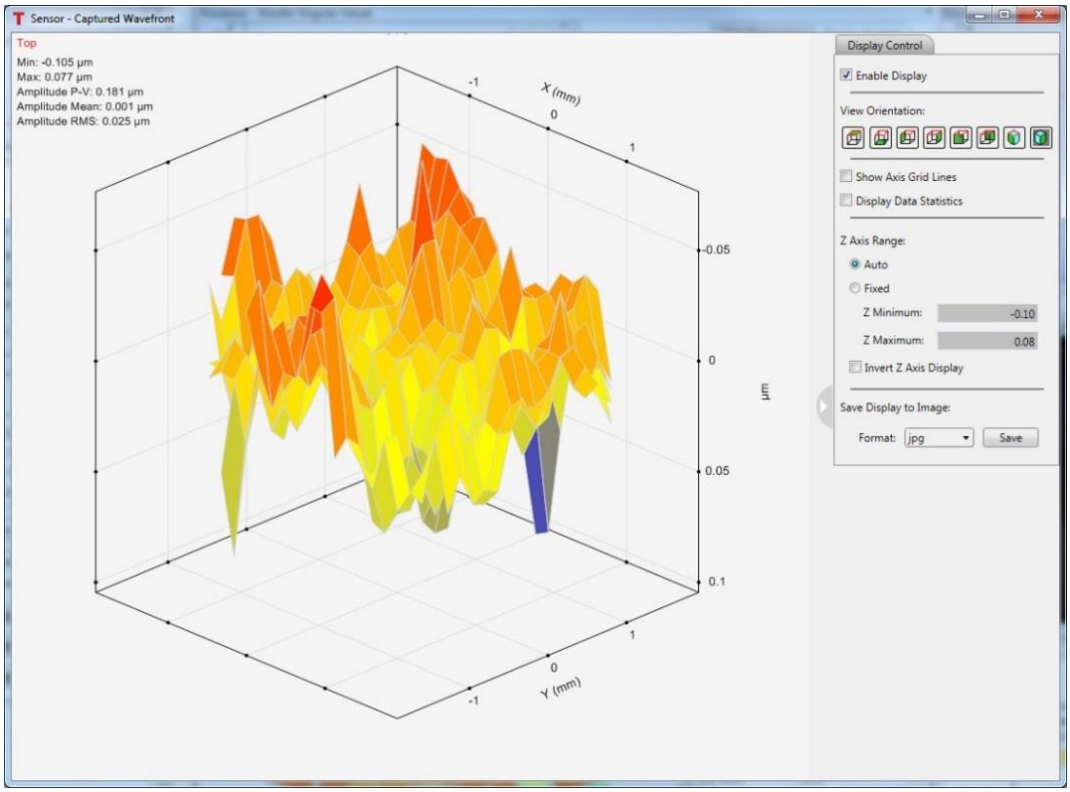


Figure 113 Wavefront Settings Window – Generated Wavefront

Wavefront Units – The user may select to display wavefront related measurements / statistics in units of **microns** or **waves** by selecting either similarly labeled radio buttons in Figure 111. Near the radio button labeled **waves**, the **wavelength** value in *nm* needs to be set to properly convert the inherent measurements (microns) to waves.

Cancel Average Wavefront Tilt – Checking this checkbox will cause the average tip/tilt contributions to the measured spot deviations to be removed before performing wavefront and Zernike calculations. This is useful since there may be small misalignment of the incident beam on the WFS microlens array and typically tip/tilt is of less interest than higher order Zernike terms.

Zernike Fit Settings

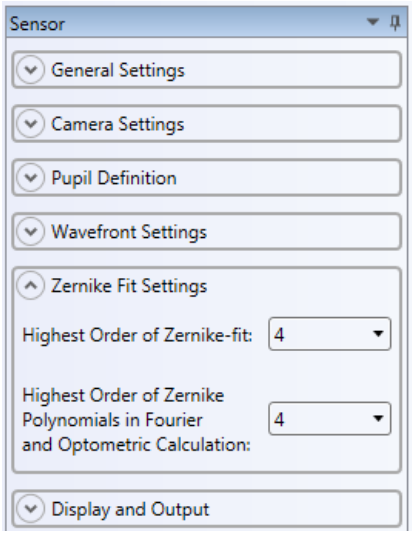


Figure 114 Wavefront Settings Window – Zernike Fit Settings

When fitting Zernike polynomials to the measured wavefront the number of Zernike terms is determined by the highest Zernike order. The default value for the highest order is 4, which results in 15 Zernike terms. See Least Square Fit Using Zernike Polynomials subsection for more information.

The AO Kit application uses the nomenclature in ANSI Z80.28-2010 for Zernike polynomials. The following is an overview of the Zernike polynomial.

Zernike Polynomial Function:

$$\boldsymbol{Z_n^m = N_n^m * R_n^{|m|}(\rho) * M(m\theta)}$$

ρ is a real number: $0.0 \leq \rho \leq 1.0$
θ is a real number: $0.0 \leq \theta \leq 2\pi$
n is the non-negative radial integer index
m is the meridional signed integer index

Radial Term:

$$\boldsymbol{R_n^{|m|}(\rho) = \sum_{s=0}^{0.5(n-|m|)} \frac{(-1)^s\,(n-s)!}{s!\;(0.5(n+|m|)-s)!\;(0.5(n-|m|)-s)!}\rho^{(n-2s)}}$$

$\rho = \frac{r}{a}$; Where *a* is the aperture radius and ρ is unitless.

Meridional Term (a.k.a. azimuthal term):

$$M(m\theta) = \cos(m\theta); for\ m \geq 0$$

$$M(m\theta) = \sin(|m|\theta); for\ m < 0$$

Normalizing Term:

$$N_n^m = \sqrt{(2 - \delta_{0,m})(n+1)}$$

Where $\delta_{0,m} = 1\ if\ m = 0$ and

$$\delta_{0,m} = 0\ if\ m \neq 0$$

For un-normalized Zernike polynomials, $N_n^m = 1.0$

Zernike Single Index Ordering:

$$Z_j = Z_n^m$$

Where $j = \frac{n(n+2)+m}{2}$

Display and Output

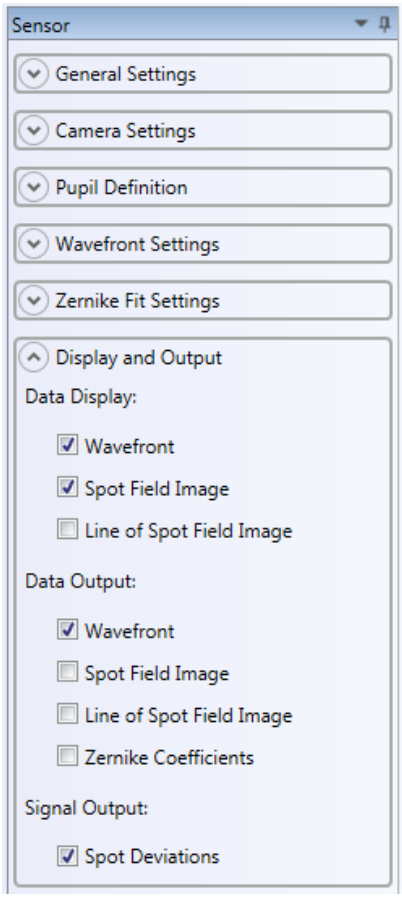


Figure 115 WFS Settings Window – Display and Output Options

Data Display – This section offers control over whether to display the graphic data window. There are three data display options for Thorlabs Wavefront sensor: **Wavefront**, **Spot Field Image** and **Line of Spot Field Image**. Checking the data display option will make the data display window visible. Unchecking this option will close the data window.

Data Output – This section offers control over whether the data will be output to a file when the control system / device is in the recording mode. There are four data output options for Thorlabs Wavefront sensor: **Wavefront**, **Spot Field Image**, **Line of Spot Field Image**, and **Zernike Coefficients**. Checking this option will output the data to a file when the control system is in recording mode.

Signal Output – This determines whether the signal used in a closed-loop control from Thorlabs Wavefront sensor will be output to a file when the control system / device is in the recording mode. By default, the signal is **Spot Deviations** measured from the Wavefront Sensor.

8.2.2.2. Thorlabs Wavefront Sensor Element Data Display

8.2.2.2.1. Wavefront Data

The wavefront data display window (Figure 116) allows the user to view the measured wavefront, as part of an independent WFS only system or an AO control system.

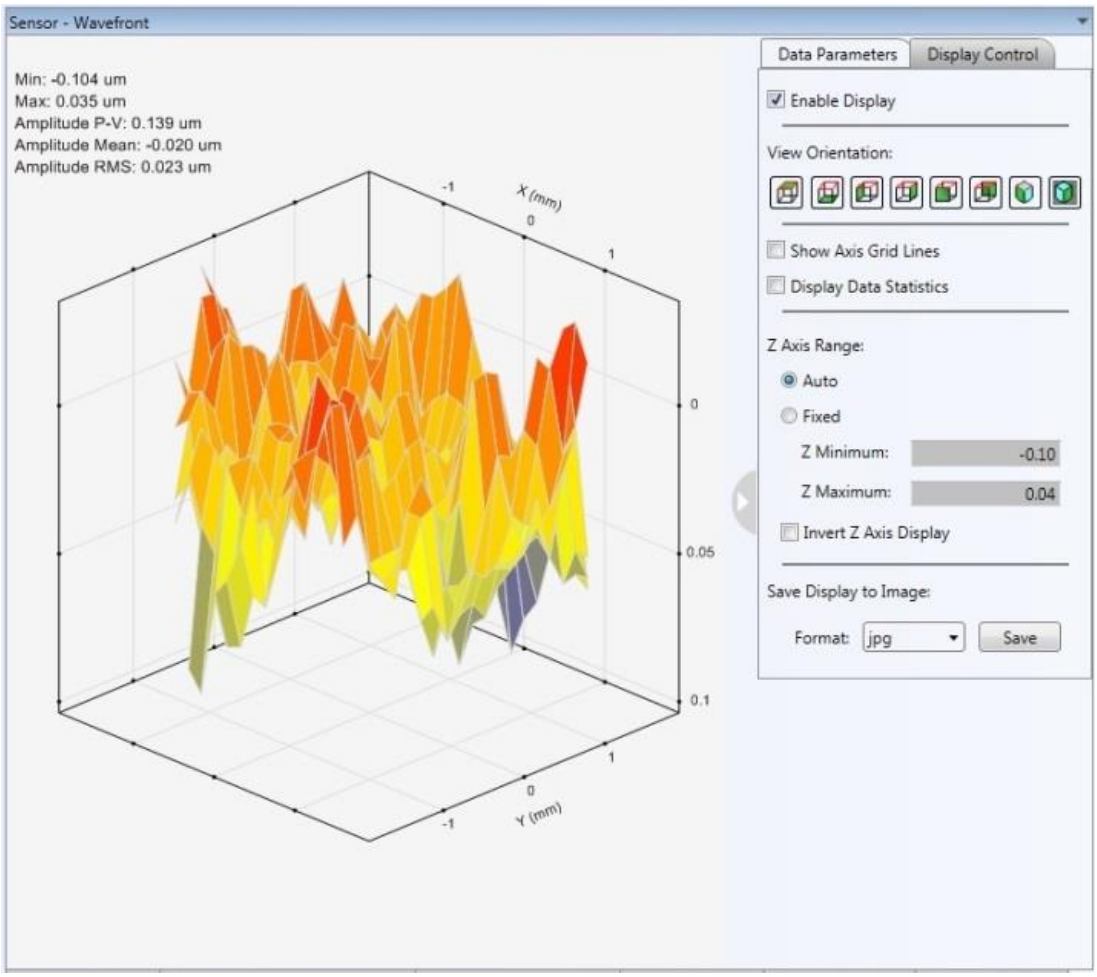


Figure 116 Wavefront Data Display Window

Working with the Surface Plot

On the left side of the window, a surface graph is used to display the Wavefront data. To manipulate the graph, click on the graph and then use the following keys to perform the selected operations.

- **Left Mouse-Button:** Drag the chart around the graph window.
- **Middle Button / Mouse Wheel Button:** Tip/Tilt, turn, and spin the graph. This is most helpful in viewing the complete wavefront.
- **Right Mouse-Button:** Click this button and drag up / down to scale the displayed surface along the z-axis.
- **Mouse Wheel:** Zooms in / out depending on which way the mouse wheel is turned.

Data Parameters Tab

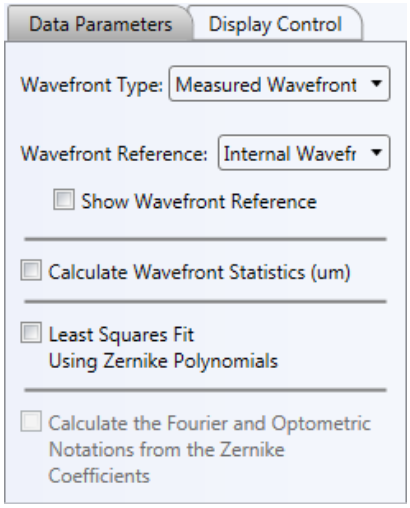


Figure 117 Data Parameters Tab for the Wavefront Data Display Window

Wavefront Types – With regard to viewing the wavefront, the user may select from three wavefront types to display: 1) measured, 2) reconstructed, and 3) difference, see Figure 118.

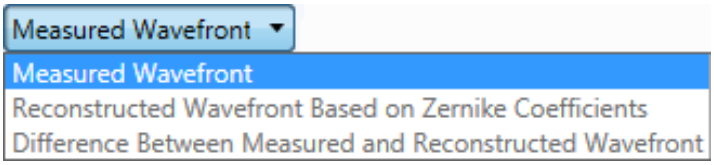


Figure 118 Wavefront Types

- **Measured:** When this option is selected, the wavefront displayed is directly calculated from the measured spot deviations using a 2-dimensional integration.
- **Reconstructed:** When this option is selected, the wavefront displayed is calculated by fitting the data based on the selected Zernike coefficients. The Zernike coefficients available for fitting are controlled by the **Zernike Fit Settings** in the Sensor plugin parameters tab and affect the available modes used to display a reconstructed wavefront.
- **Difference:** When this option is selected, the displayed wavefront is the difference between the measured and the reconstructed.

The 2nd and 3rd option may be disabled. To enable these two options, the checkbox of **Least Squares Fit Using Zernike Polynomials** must be checked. See section **Least Square Fit Using Zernike Polynomials**.

Wavefront Reference – There are four wavefront reference options, see Figure 119.

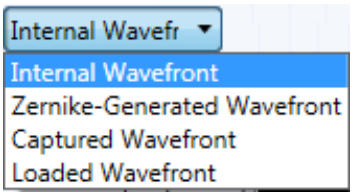


Figure 119 Wavefront Reference Types

- **Internal Wavefront** – The internal wavefront reference is set via calibration during the manufacturing process. It is written into the WFS's internal memory, EEPROM.

- **Zernike Generated Wavefront** – A Zernike-based reference wavefront may be generated using the **Use Zernike Polynomials** button under the **Wavefront Settings** section of the Sensor element tab, see Figure 111.

- **Captured Wavefront** – A measured wavefront may be used as a reference wavefront. To capture a wavefront use the **Capture Active Wavefront** button under the **Wavefront Settings** section of the Sensor element tab, see Figure 111.

- **Saved Wavefront** – Any measured or generated (Zernike-based) wavefront may be saved and loaded to use as a reference wavefront. To load a saved wavefront, use the **Load Wavefront from File** button under the **Wavefront Settings** section of the Sensor element tab, see Figure 111.

Calculate Wavefront Statistics – Checking this checkbox will display the minimum, maximum, mean and RMS statistics for the measured wavefront. See Figure 120.

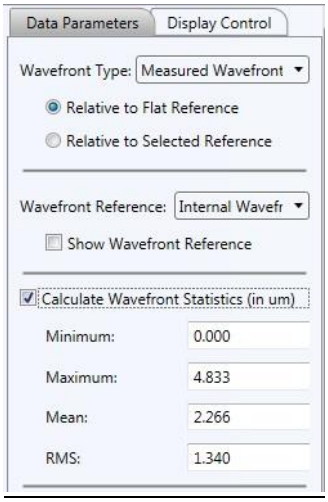


Figure 120 Calculated Wavefront Statistics

Least Square Fit Using Zernike Polynomials – Checking this checkbox will display a list of Zernike terms and the measured Zernike RMS values (coefficients) for the measured wavefront, as well as the RMS variation per Zernike order. Figure 122 shows the result of checking this box. The number of Zernike orders, and the related polynomial terms is controlled by the value set for the **Highest Order of Zernike-fit** within the **Zernike Fit Settings** section in

the Sensor element tab (see Figure 115). It also allows one to monitor the measured Zernike coefficients. The coefficients are calculated using the least squares fit method and are displayed in units of microns or waves. The units are set in the **Wavefront Settings** section in the Sensor element tab, see Figure 111.



Figure 121 The Least Squares Fit using Zernike polynomials

The checkboxes to the left of the Zernike terms are used (checked) to select the terms for calculating the reconstructed wavefront when the displayed wavefront type is set to **Reconstructed** or **Difference**. The values displayed to the right of the Zernike terms do not change based on the selected terms. The values are based on the least squares fit of the measured Shack-Hartman spot deviations. See the WFS User's Manual for more details.

Calculate the Fourier and Optometric Notations from the Zernike Coefficients - The parameters associated with the Fourier and Optometric Notations are explained in a paper titled "*Analysis of refractive errors in the human eye using Shack Hartmann Aberrometry*", by M. Jesson, P. Arulmozhivarman, and A.R. Ganesan. The paper was uploaded to Research Gate by the author P. Arulmozhivarman on 18-Aug-2015 (https://www.researchgate.net/publication/266471430). These parameters are **FourierM** (spherical equivalent power), **FourierJ45** (the power of Jackson cross-cylinder with its axis set at 45 degrees) and **FourierJ0** (the power of Jackson cross-cylinder with its axis set at 0 degrees).

The optometric parameters C (**OptoCylinder**), S (**OptoSphere**), and A (**OptoAxisDeg** (Angle)) are functions of the three Fourier parameters noted above.

To enable this calculation, the **Least Square Fit Using Zernike Polynomials** must be checked.

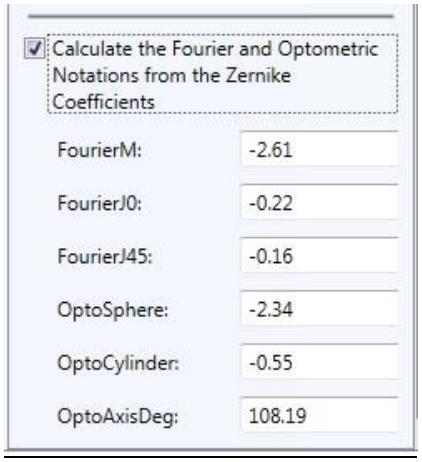


Figure 122 The Fourier and Optometric parameters are displayed when the checkbox is checked.

Display Control Tab

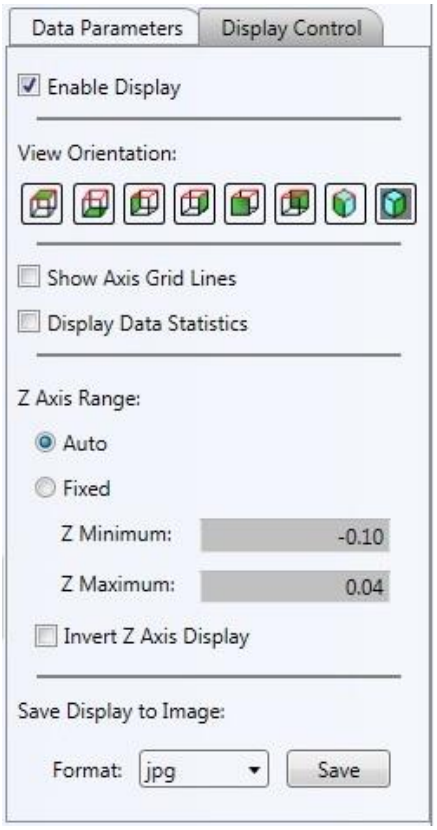


Figure 123 Display Control tab for the Wavefront Data Display Window

Enable Display – Checking this box activates the data in the wavefront window to update. Unchecked, it reduces MS Windows resources used for graphic updates.

View Orientation – Selecting one of the icons in this section will change the orientation of the wavefront graphical display. The options are, from left to right, to view from top, bottom, right, left, front, back, front-right-top, and front-left-top.

Show Axis Gridlines – Sets whether gridlines in the XY, YZ, and XZ planes are visible, or not.

Display Data Statistics – Sets whether the statistics for the measured wavefront are displayed in the upper left corner of the wavefront graphics window. The statistics include minimum, maximum, P-V, mean, and RMS.

Z-Axis Range – The controls in this group enable the Z-axis range to be set to auto scale or be fixed. If fixed, the minimum and maximum values may be set manually.

Save Display to Image – The graphical wavefront image may be saved. There are four image formats available: jpg, bmp, tif, or png. Clicking the Save button will display a standard MS Windows save file dialog box, in which one may navigate to the folder to save the image.

8.2.2.2.2. Spot Field Image Data Display Window

The spot field data display window shows the direct view of the image taken by the Wavefront Sensor. Intensity levels are displayed as gray scale levels from 0 (black) to 254 digits (white), while saturated pixels are displayed in red.

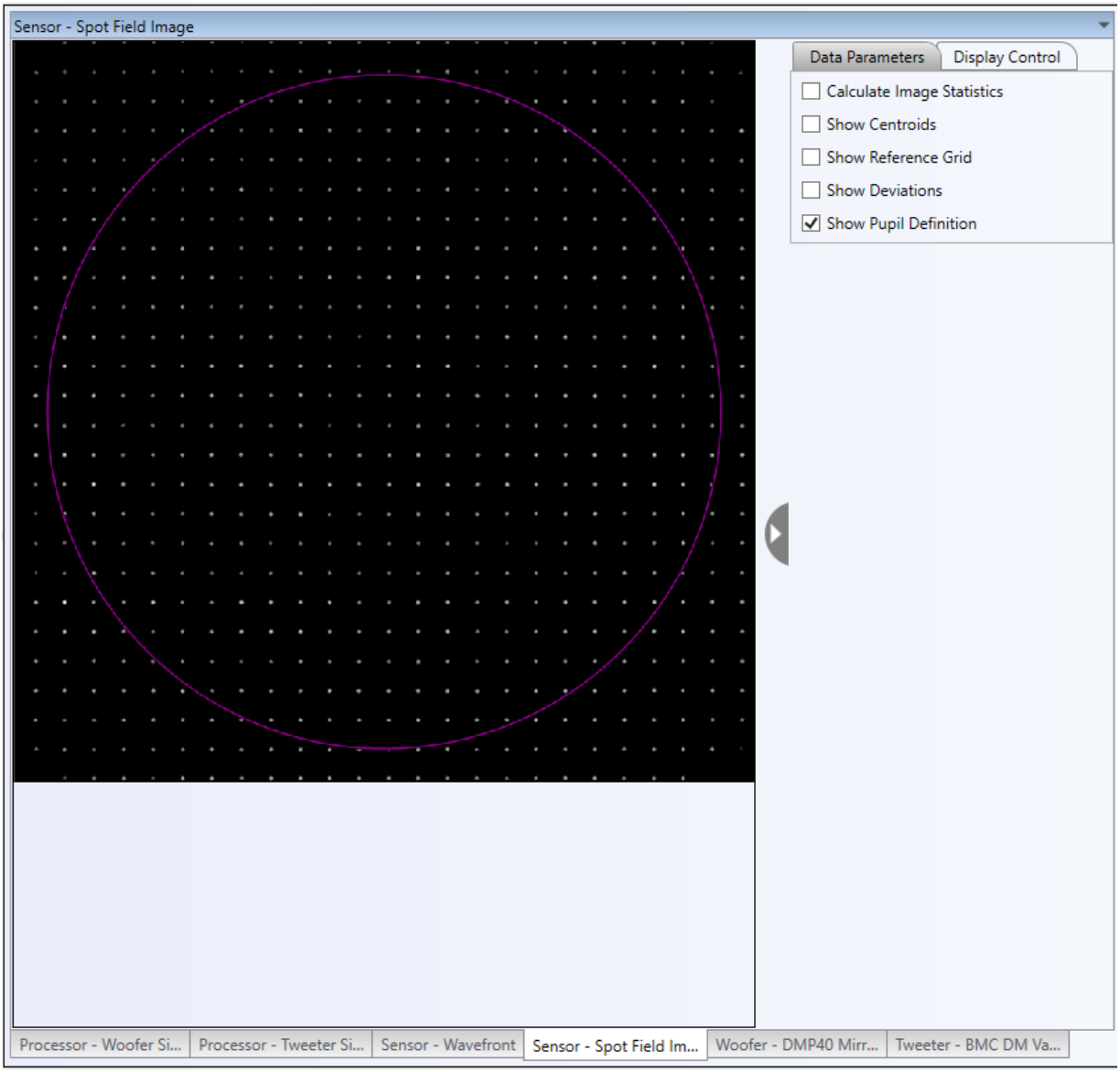


Figure 124 Wavefront Sensor Spot Field Image Window

Data Parameters Tab

Calculate Image Statistics – When this box is checked, statistics related to the spot intensity will display under the checkbox, see Figure 126. The statistics include minimum, maximum, means, RMS intensity. Additionally, the percent of total pixels that are saturated is displayed.

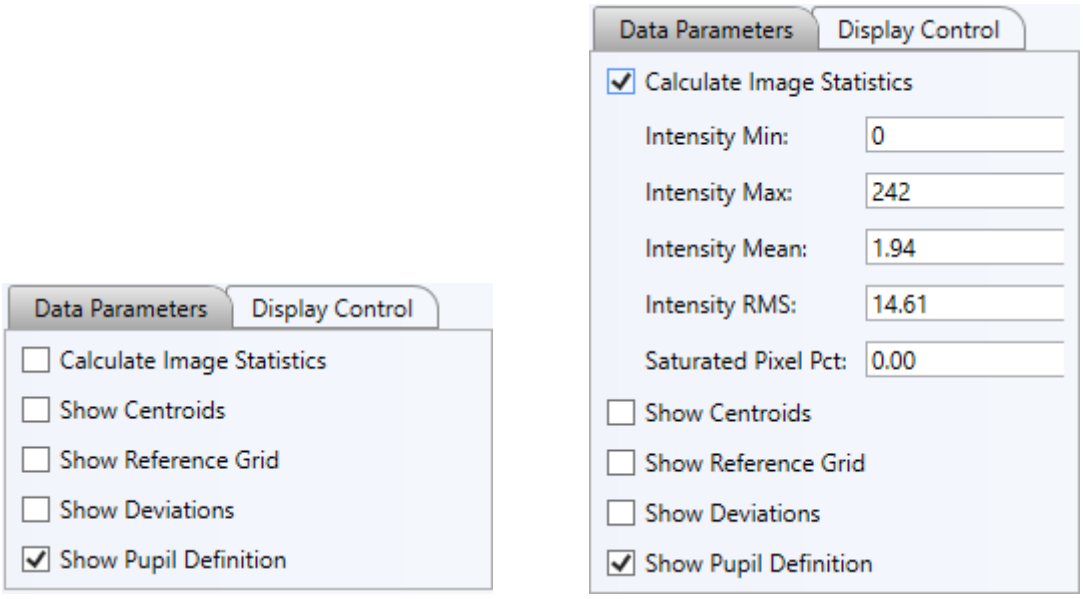


Figure 125 Spot Field Image Window Data Parameters Tab

Show Centroids – Checking this option will display the centroid of each member of the spot field pattern.

Show Reference Grid – Checking this option will display the spot field pattern corresponding to the reference wavefront.

Show Deviations – If checked, a short line appears connecting each centroid spot with its corresponding reference spot.

Show Pupil Definition – Checking this option will display the pupil over the spot field image.

Display Control Tab

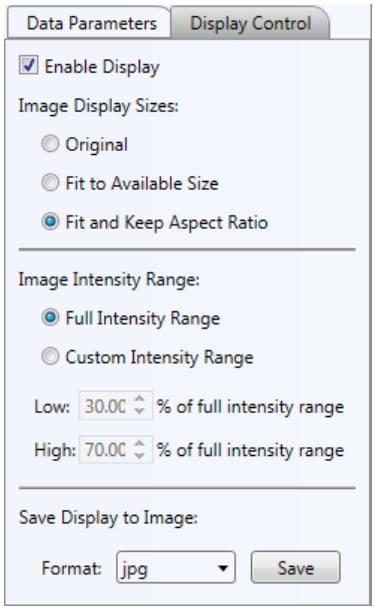


Figure 126 Spot Field Image Window Display Control Options

Enable Display – Checking this box activates the data in the Spot Field Image display window to update. Unchecked, it reduces MS Windows resources used for graphic updates.

Image Display Sizes

- **Original** – 1:1 match between the WFS image pixels and display pixels. If the WFS image size is 768x768 pixels, then the image will use 768x768 monitor pixels. If the image size is larger than the display container, horizontal and or vertical scroll bars will appear.
- **Fit to Available Size** – The WFS image is scaled to match the display container.
- **Fit and Keep Aspect Ratio** – While keeping the aspect ratio constant, the WFS image is scaled to fit the display container.

Image Intensity Range – These controls affect the spot field image, on a pixel by pixel basis.

- **Full Intensity Range** – Selecting this option uses the full intensity range of the WFS camera.
- **Custom Intensity Range** – With this option selected, a lower and high intensity range may be manually set. Any pixel value with an intensity value less than the lower threshold will appear black, while any pixel with an intensity value above the high threshold will appear white (saturated).

Save Display to Image: The graphical wavefront image may be saved. There are four image formats available: jpg, bmp, tif, or png. Clicking the Save button will display a standard MS Windows save file dialog box, in which one may navigate to the folder to save the image.

8.2.2.2.3. Spot Field Line Data Display Window

The spot field line data display shows the intensity of each pixel along a row (horizontal) of the WFS CCD (CMOS) sensor. Figure 127 shows an example of the display.

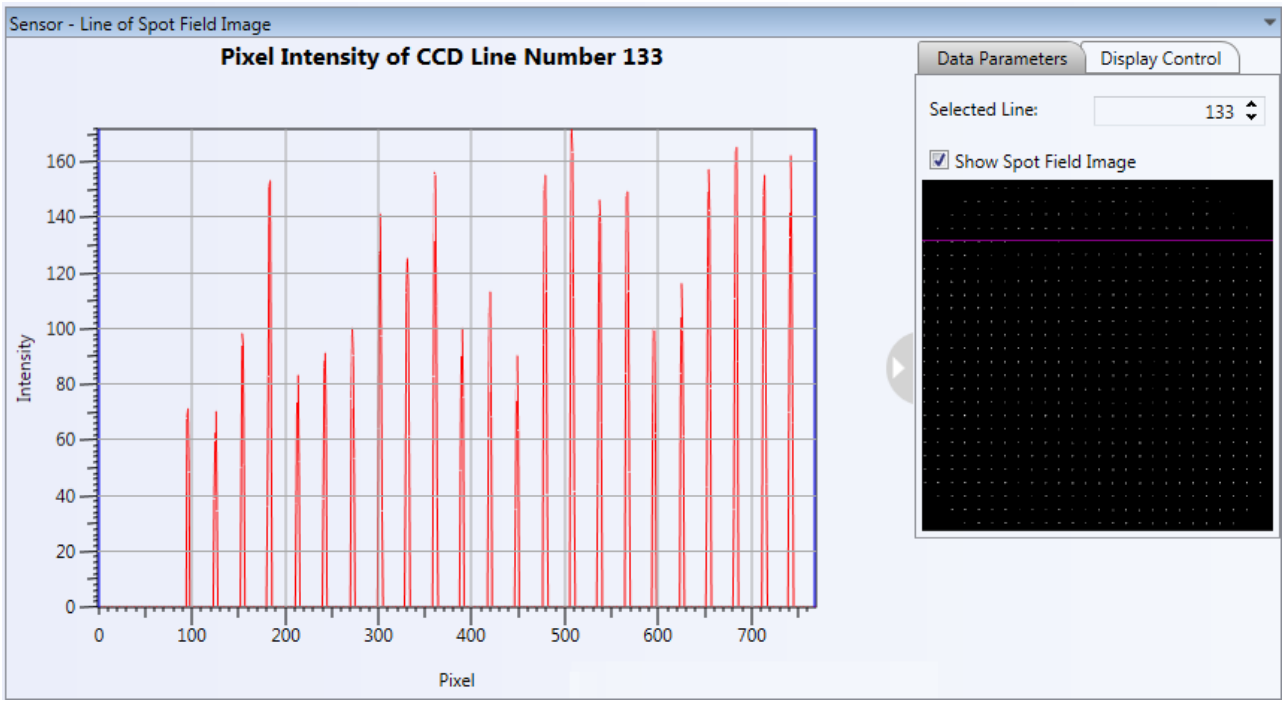


Figure 127 WFS Line of Spot Field Image Window with the Data Parameters

Data Parameters Tab

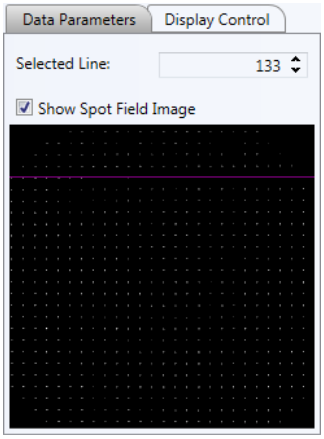


Figure 128 WFS Spot Field Image Window Data Parameters Tab

Selected Line – The Data Parameter tab contains controls to select the horizontal set of CCD (CMOS) pixels whose intensities will be displayed in the graphic area. The numeric control labeled Selected Line is used to select the row number, row 1 is at the top of the image. The horizontal red line indicates the selected row.

Show Spot Field Image – Checking this box will display the spot field image below. Left unchecked, the image will not be displayed.

Display Control Tab

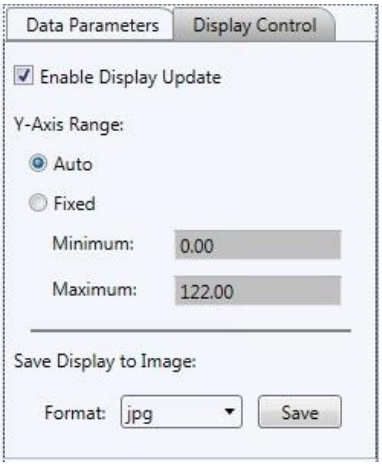


Figure 129 WFS Spot Field Image Window Display Control Tab

Enable Display – Checking this box activates the data in the Spot Field Line Data display window to update. Unchecked, it reduces MS Windows resources used for graphic updates.

Y-Axis Range

- **Auto**: Selecting this option allows the y-axis range to auto scale.
- **Fixed**: This option allows the y-axis **Minimum** and **Maximum** values to be set manually.

Save Display to Image - The graphical wavefront image may be saved. There are four image formats available: jpg, bmp, tif, or png. Clicking the Save button will display a standard MS Windows save file dialog box, in which one may navigate to the folder to save the image.

8.2.3. Controller Element - Thorlabs DMP40

The DMP40-P01 (DMP40/M-P01) deformable mirror element window is laid out into two (2) sections. The left section is element tab which includes deformable settings and display/output settings. The right section is the graphical display of the mirror segments and arms, see Figure 130. The mirror includes the main mirror segments that are used to affect the incident wavefront. There are 40 unimorph piezoelectric actuators arranged in a radial pattern to allow the application of Zernike based shapes to the mirror surface. These segments are physically separate from the DMP40 design's three (3) bimorph arms used to affect overall tip and tilt of the mirror.

The mirror segments are controlled by applying a voltage, 0 - 200 V, to each segment. The mirror is nominally flat when there is approximately 100 V applied to all the segments. The arms are controlled by applying a voltage, 0 - 200 V, with the initial voltage of 0 V, no tip / tilt applied.

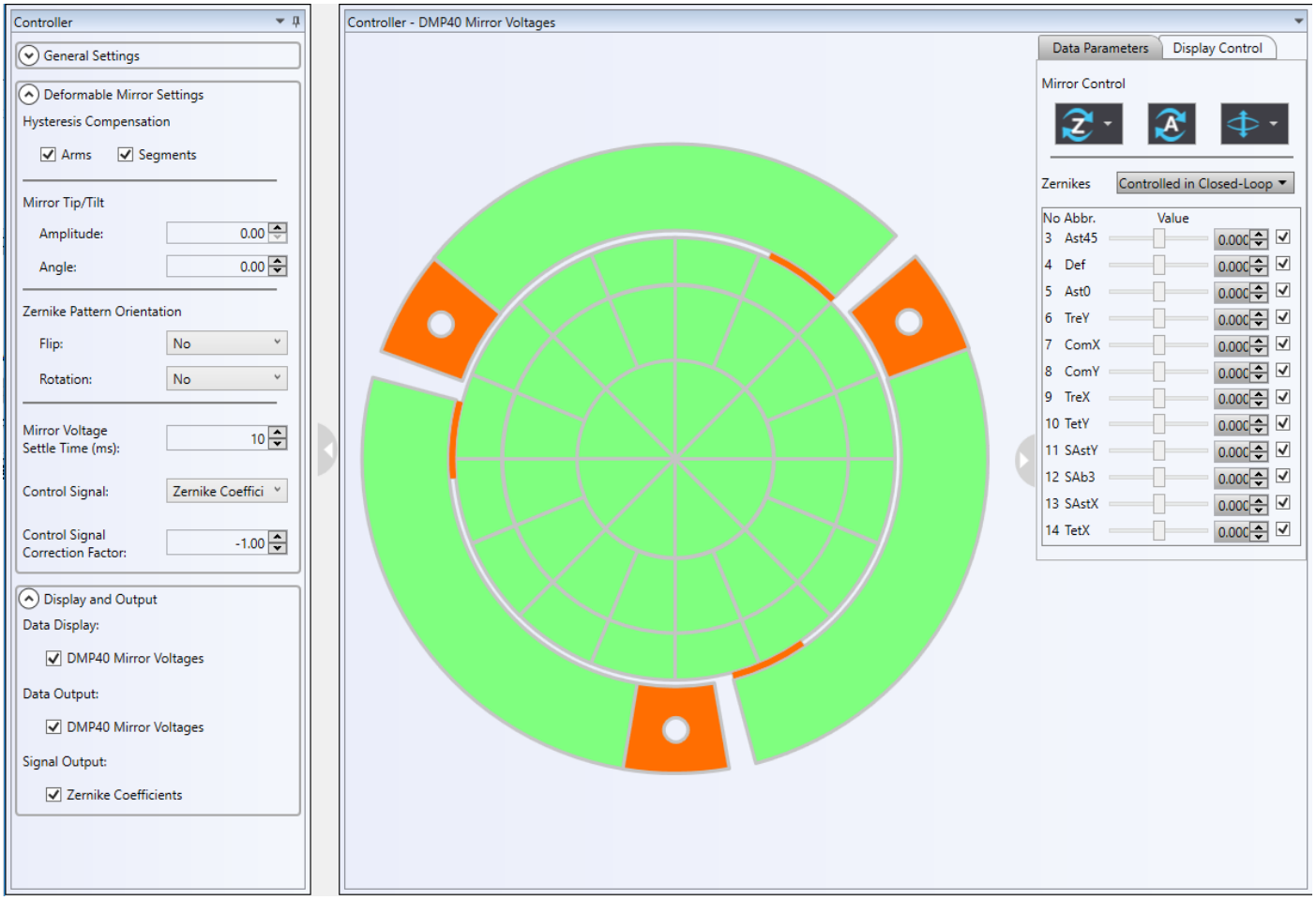


Figure 130 Thorlabs DMP40 Element Tab and Graphics Data Panel

8.2.4. Controller Element – Thorlabs DMH40

The DMH40-P01 (DMH40/M-P01) deformable mirror element window is laid out into two (2) sections. The left section is element tab which includes deformable settings and display/output settings. The right section is the graphical display of the mirror segments, see Figure 131. The mirror includes the main mirror segments that are used to affect the incident wavefront. There are 40 unimorph piezoelectric actuators arranged in a radial pattern to allow the application of Zernike based shapes to the mirror surface

The mirror segments are controlled by applying a voltage, 0 - 300 V, to each segment. The mirror is nominally flat when there is approximately 150 V applied to all the segments. The arms are controlled by applying a voltage, 0 - 300 V, with the initial voltage of 0 V.

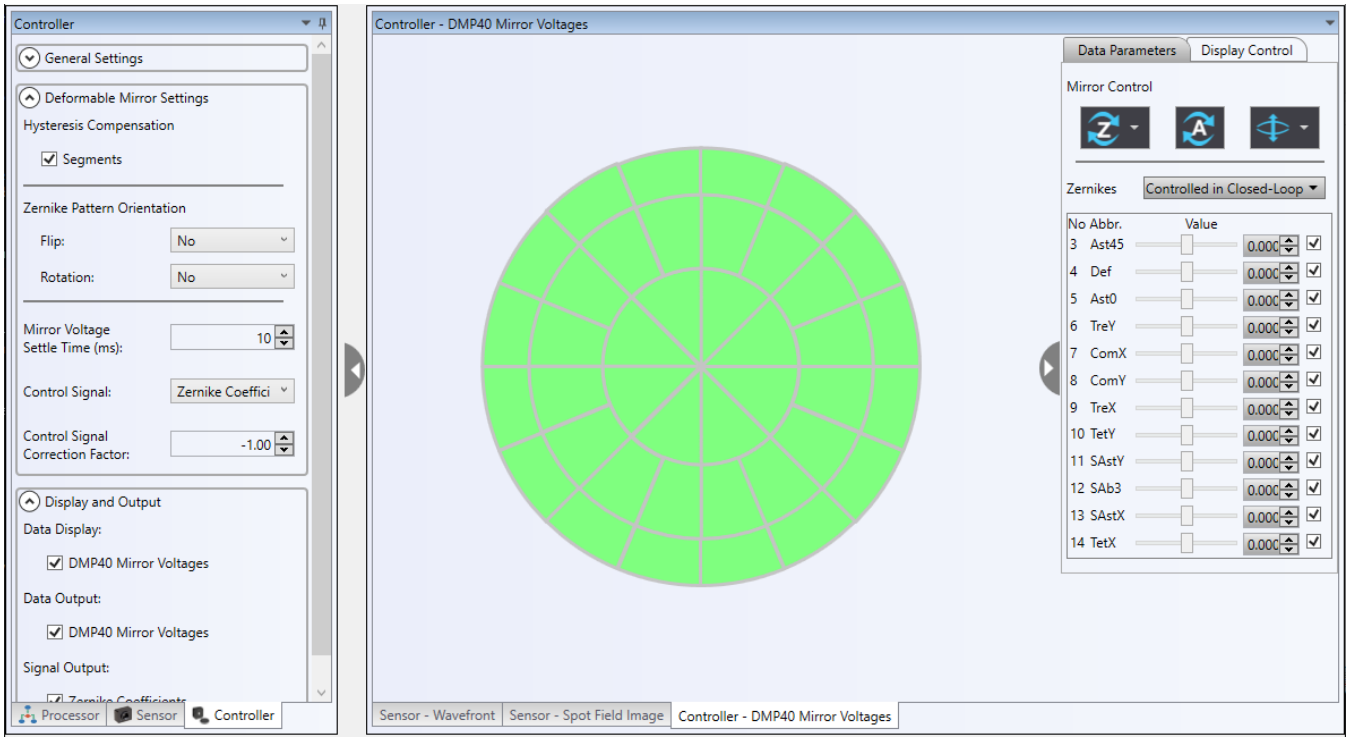


Figure 131 Thorlabs DMH40 Element Tab and Graphics Data Panel

8.2.4.1. Thorlabs DMP40 or DMH40 Controller Element Parameters Tab

The Thorlabs DMP40 or DMH40 settings are grouped into three categories: General Settings, Deformable Mirror Settings, and Display and Output. Each group will be detailed below.

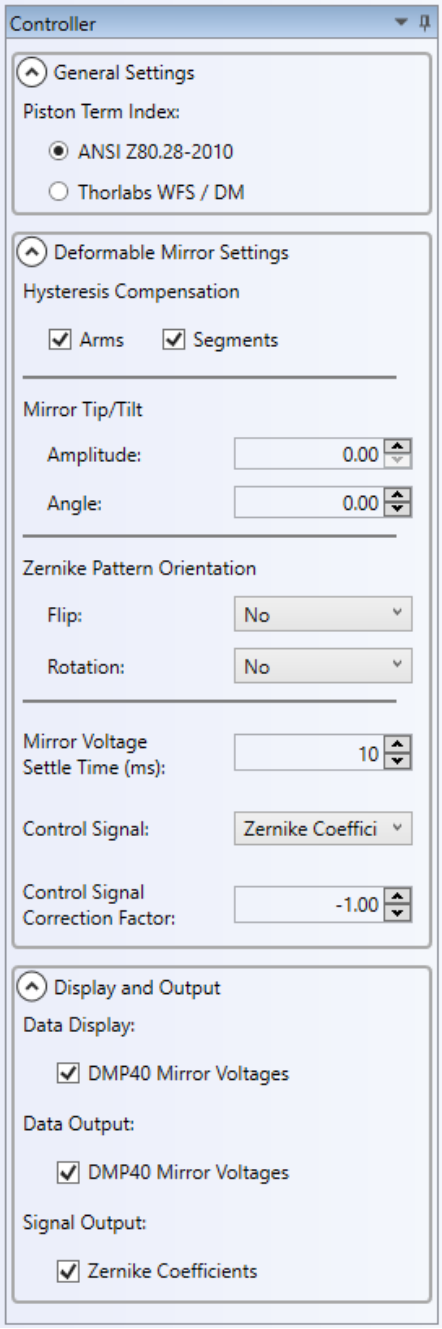


Figure 132 Thorlabs DMP40 Tab (DMH excludes the Tip/Tilt control)

General Settings

Piston Term Index - Defines the Zernike monomials order. Two options: ANSI Z80.28-2010 or Thorlabs' definition used in WFS and DM.

Deformable Mirror Settings

Hysteresis Compensation - This checkbox allows the user to independently enable (checked) or disable (not checked) hysteresis compensation for the arm actuators and the segment actuators. The hysteresis compensation function is part of the DMP40 or DMH40 DLL function set. For more information on this function, please see the DMP40 or DMH40 operator's manual and/or the DLL function manual. The DLL function manual is an html file that is typically found in folder *C:\Program Files (x86)\IVI Foundation\VISA\WinNT\TLDFM\Manual*.

Mirror Tip/Tilt - In addition to controlling the arm voltages individually, the arms may be controlled simultaneously to define a tilt amplitude and the angle of an axis in the plane of the un-tilted mirror that goes through the center of the mirror about which the mirror is tilted. See Figure 133.

- **Amplitude** - Works with the **Tilt** control and sets the relative amplitude of the mirror tilt, 0 - 100%. See Figure 133 below for the physical definition of the Tilt Amplitude.

- **Angle** - Works with **Amplitude** control to affect the voltages to the three control arms simultaneously to cause the mirror to tilt about an axis defined by the Tilt Angle. It can be set to a value from -180 to +180 degree. See Figure 133 below for the physical definition of the Tilt Angle.

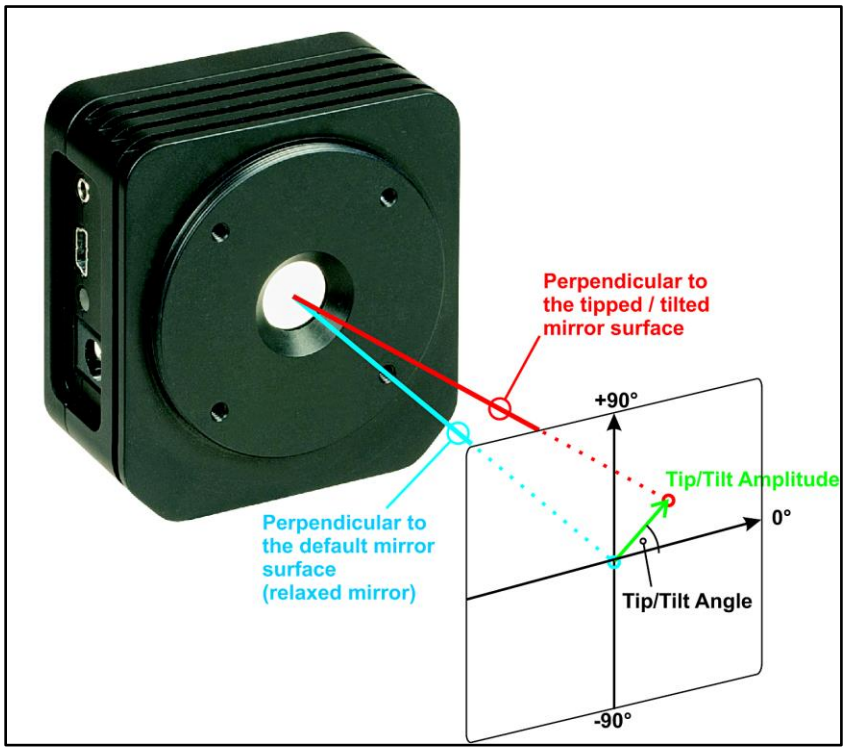


Figure 133 DMP40 Tip and Tilt Angle Explanation

Zernike Pattern Orientation - Following a ray's projection through an optical system, its components and layout may flip and or rotate the reference frame of the ray. With the objective of matching the frame of the DM and a wavefront sensor, the DMP40 or DMH40 control panel includes the ability flip and rotate the reference frame of the Zernike shapes applied to the DM to match those measured by a wavefront sensor.

As seen in Figure 134, there are four (4) flip options: **No**, **Horizontal**, **Vertical** and **Both Horizontal and Vertical**. There are also four (4) options for rotation: **No**, **45 degrees**, **90 degrees**, and **135 degrees**.

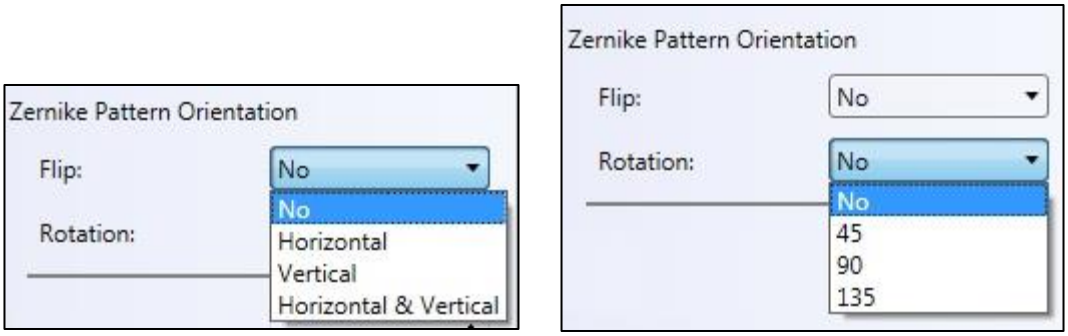


Figure 134 DMP40 or DMH40 Flip and Rotation for Zernike Patterns

Mirror Voltage Settle Time (ms) - This is the time, in milliseconds, the system pauses before continuing after a change to the DM voltage map is made, allowing the DM Piezo segments to settle into their final position.

Control Signal - In a control system, the mirror is controlled using **Zernike coefficients**.

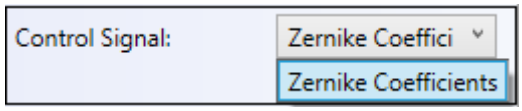


Figure 135 In a closed-loop control system, the DMP40 or DMH40 is controlled by Zernike coefficients.

Control Signal Correction Factor - The control system correction factor is a gain value applied to the closed-loop control correction signal. The default is -1.

Display and Output

Data Display - The checkbox labeled **DMP40 Mirror Voltages** allows one to display or not display the Controller - DMP40 or DMH40 Mirror Voltage window.

Data Output - Checking the checkbox labeled **DMP40 Mirror Voltages** sets the voltages to be output to a data file, or not when the control system is in recording mode for the DMP40 or DMH40.

Signal Output - This determines whether the signal used to control Thorlabs DMP40 or DMH40 Deformable Mirror in a closed-loop control will be output to a file when the control system / device is in the recording mode. By default, the signal is **Zernike Coefficients**.

8.2.4.2. Thorlabs DMP40 or DMH40 Controller Element Data Display

For the Thorlabs DMP40 or DMH40 deformable mirror, there is one data display, the Mirror Voltages. Reference figure 136.

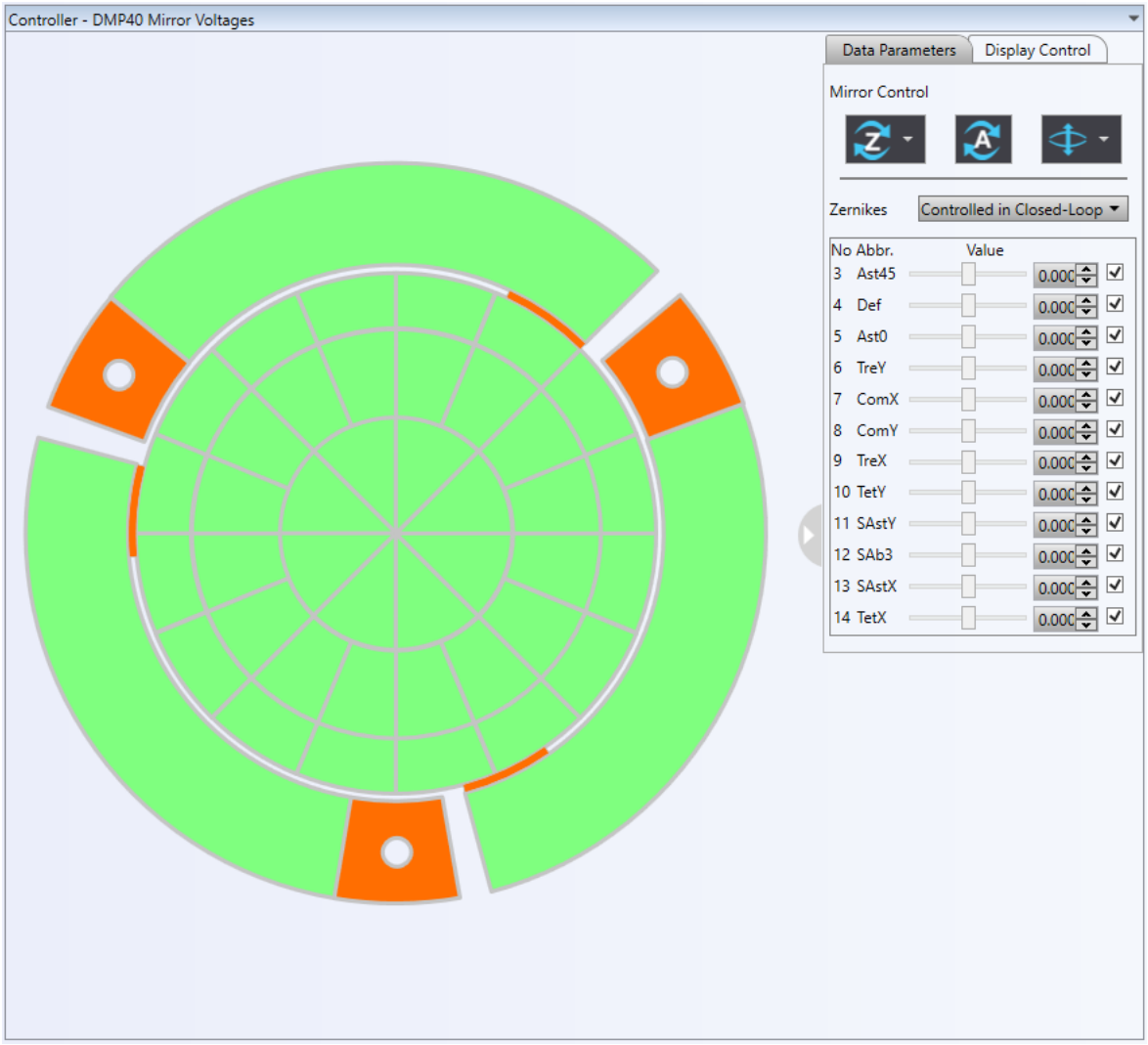


Figure 136 DMP40 Mirror Voltages Display Window (DMH40 does not have the 3 tip-tilt actuators)

Data Parameter Tab



The Zernike button: Checking this button will display a drop-down menu with three (3) options:

- **Home Zernikes**. This will set all Zernike coefficients (slider values) to zero (0). Voltages set to individual actuators will remain, only the voltages related to the applied Zernike coefficients will be set to zero.
- **Load Zernikes**. This will open a standard file open window for one to load the Zernike coefficients from a file and set the values to the sliders. The new Zernike pattern will be calculated and the new voltages will be applied to individual actuators.
- **Save Zernikes**. This will save the current Zernike coefficients to a file.



The **Reset All button**: This will reset all the Zernike coefficients to zero, and all the inner segment voltages to 100 V (DMP40) or 150 V (MDH40).



The **Relax button**: The relax function applies a prescribed sequence of voltages to the mirror segments and/or arms to remove the mechanical stresses in the piezo electric actuators. The final segment and/or arm voltages remain the same as they were before the relax function is applied.

Clicking this button will display a drop-down menu with three (3) options:

- **Relax All** relaxes both arms and inner segments.
- **Relax Segments** only relaxes the inner segments.
- **Relax Tip/Tilt Arms** only relaxes the arms.

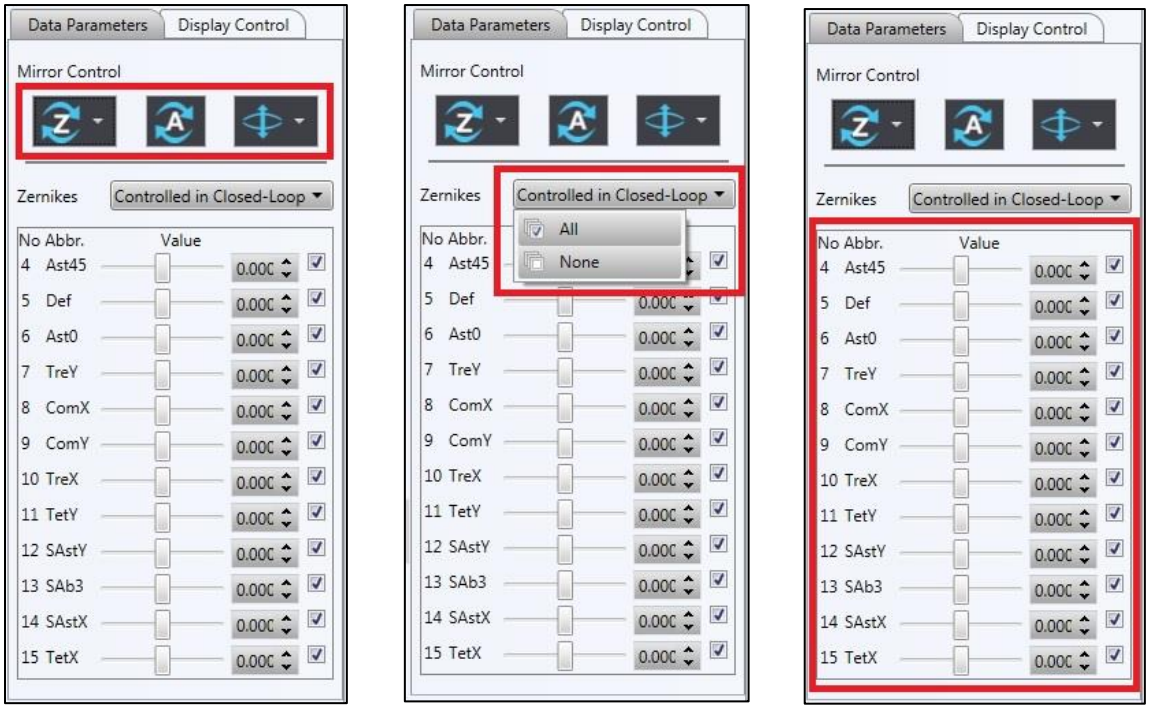


Figure 137 Data Parameters Tab: (Left) Relax and Reset Mirror Actuators and (Center & Right) Select Zernike Terms to Include in Closed-Loop Control

Controlled in Closed-Loop - A drop-down menu that allows one to select all or none of the Zernike terms to be used during the closed-loop control process.

Zernike Coefficient Controls - The lower region of the Data Parameters tab contains 12 sets of slider / numeric controls, one for each Zernike coefficient from Z4 through Z15 (Figure 137 right image).

Enable Checkbox controls to the right of the numeric controls allows a user to include (checked) or not include (unchecked) the specific Zernike term during closed-loop control when DMP40 or DMH40 is used in an AO control system.

In the DMP40 or DMH40 DLL there are Zernike coefficient variables used by a function to apply voltage sets to the 40 main piezo actuators to induce a Zernike shape on the mirror. The allowed relative value for these variables is ±1.0. The **Horizontal Slider** controls are set with a min/max of -1/+1 (-100%/+100%). With the DMP40/DMH40 in an AO system, after the system is calibrated, the values may be changed from relative values to absolute values via the radio buttons at the bottom of the Zernike Terms region.

The value of the slider control is displayed in the **Numeric Control Boxes**. The value of the slider control can be changed by changing the value directly by entering the new value, adjusting the up and down arrows or moving the slider.

Display Control Tab

Enable Display - Checking this box enable display updating. With it unchecked, the actuator display will not be updated as applied voltages are changed. If one clicks into segment and changes the voltages manually, they will affect the mirror actuators.

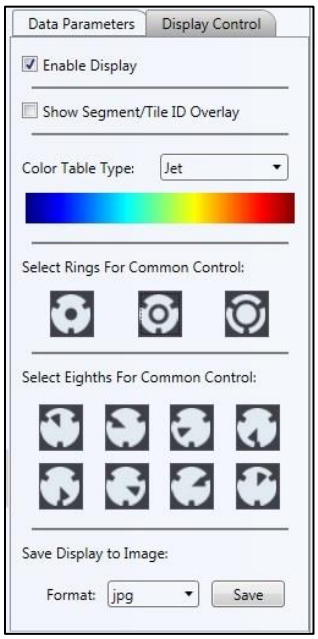


Figure 138 Display Control Tab and its Controls

Show Segment/Tile ID Layer - When this box is checked the segment and arm ID numbers are superimposed on the DM actuator graphic. See Figure 139.

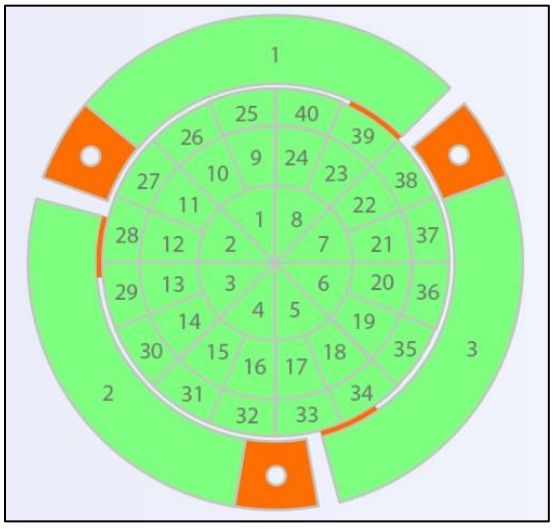


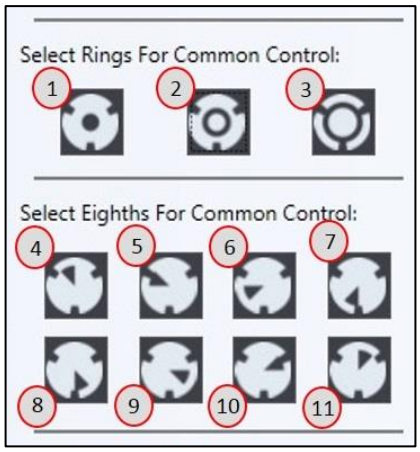
Figure 139 With the Segment/Tile ID activated, the segment and arm ID numbers are superimposed on the mirror display.

Color Table Type drop down menu:



Figure 140 Color Type Options

Mirror Control: Figure 141 shows the lower section of the Display Control tab. By clicking any of the icons labeled 1 through 11 the perimeter of the associated segments in Figure 142 will be highlighted red. Figure 142 shows the red highlighted segment edges after icon 5 is selected. If the icon is clicked again the segments will be deselected.



Eighths Sections	
Number	**Segments**
4	1, 9, 10, 25, 26
5	2, 11, 12, 27, 28
6	3, 13, 14, 29, 30
7	4, 15, 16, 31, 32
8	5, 17, 18, 33, 34
9	6, 19, 20, 35, 36
10	7, 21, 22, 37, 38
11	8, 23, 24, 39, 40

Ring Selection		
Number	**Ring**	**Segments**
1	Inner	1 through 8
2	Middle	9 through 24
3	Outer	25 through 40

Figure 141 Selecting Groups of Actuator Segments

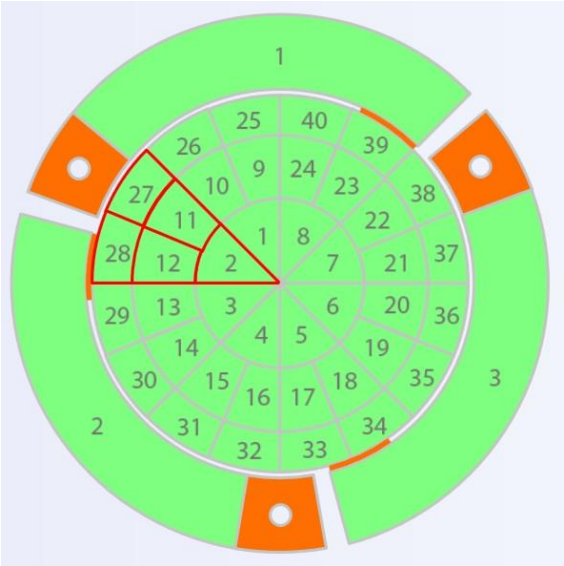


Figure 142 Segment Group 5 Selected, Actuator Segments Highlighted Red

Save Display to Image - The displayed graphical image of the segment and arms may be saved in four different image formats, jpg, bmp, tif or png. Figure 143 shows the dropdown menu used to select the format. Clicking the Save button will pop up a window to select the folder location and filename.

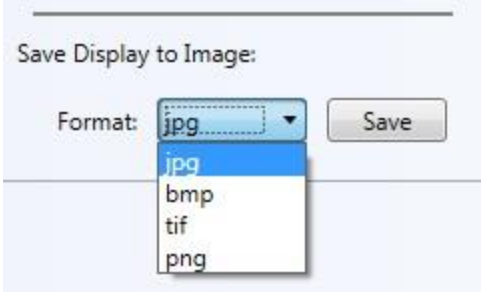


Figure 143 Four Image Formats

8.2.5. Controller Element - BMC Multi / Mini Deformable Mirror

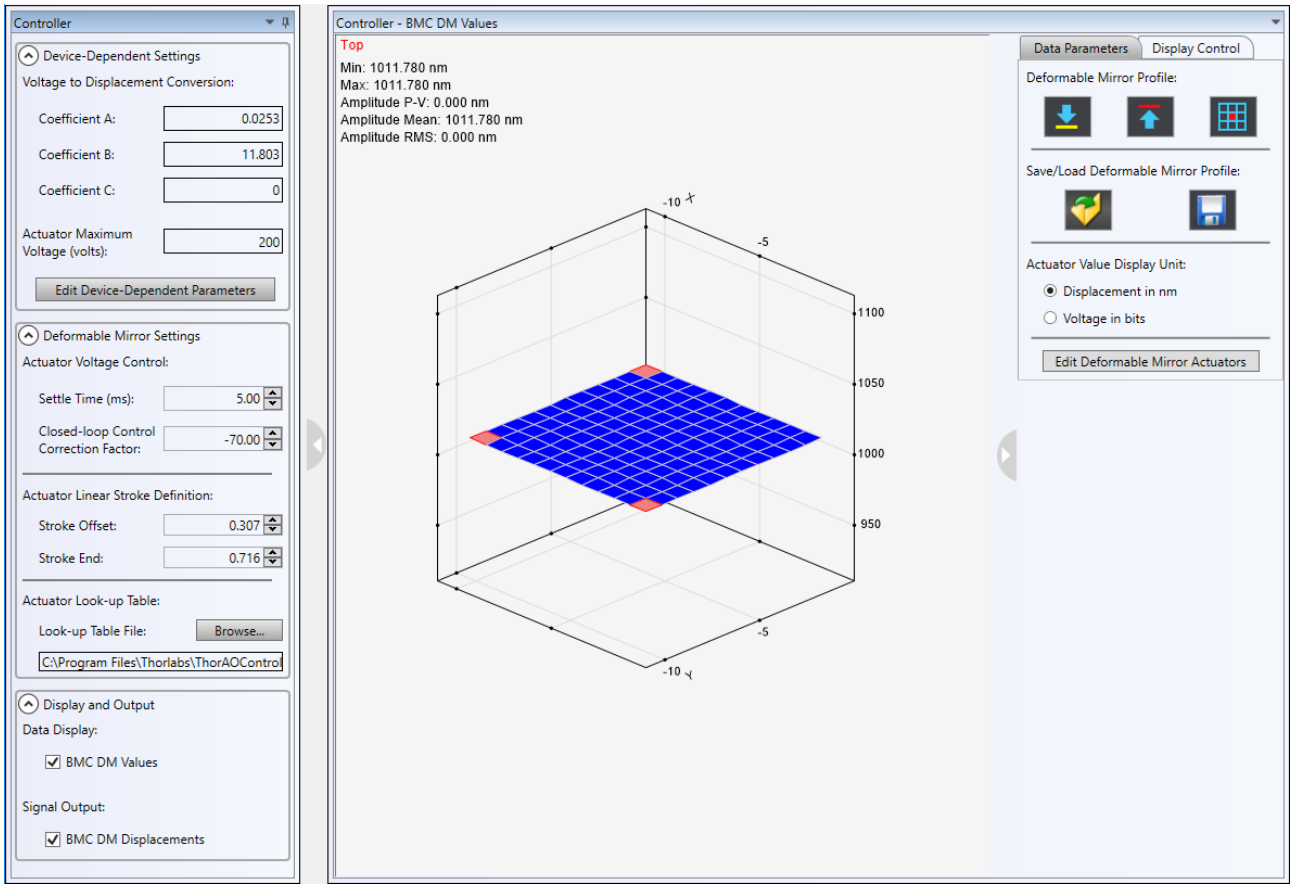


Figure 144 BMC Deformable Mirror Element Tab and Graphic Data Panel

8.2.5.1. BMC DM Controller Element Parameters Tab

The BMC DM Controller tab has three (3) sections: 1) Device Dependent Setting, 2) Deformable Mirror settings, and 3) Display and Output. Each section will be separately addressed here.

Device Dependent Settings

To properly control the deformable mirror, the software must be configured for the DM's maximum voltage and response coefficients. When initially run, all the device-dependent parameters are set to zero. There will be a button **Edit Device-Dependent Parameters** at the bottom of this section that has its border blinking red indicating a new system has been setup and the DM coefficients and max voltage needs to be set (See Figure 145(a)). After the device specific values have been set/modified, the button **Confirm Device-Dependent Parameters** will be blinking red to indicate that the new values need to be verified, see Figure 145(b). Once all the values have been confirmed, the button **Confirm Device-Dependent Parameters** will be hidden from the section (See Figure 145(c))

IMPORTANT NOTE

The flashing red button titled Confirm Device Dependent Parameters will automatically appear each time a control system is started that includes a BMC DM for which the coefficients and maximum voltage have not been verified/confirmed. This is intended to remind the user that these parameters must be changed if the DM has been set and confirmed, thereby minimizing the chance of inadvertently damaging the DM.

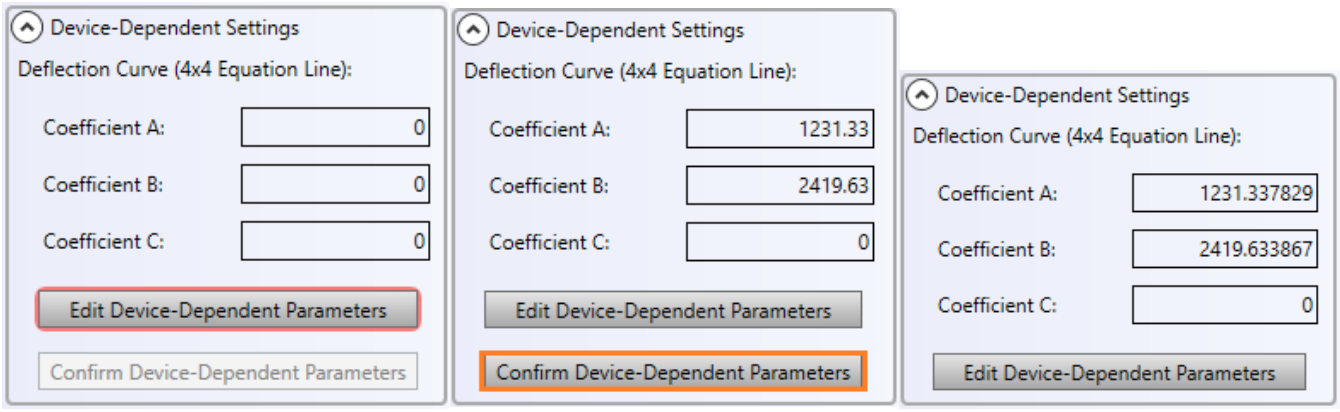


Figure 145 Device Dependent Settings Section: (a) All the parameters are set to zero when initially run. A red flashing button indicates a new system has been setup and the parameters need to be set. (b) This button confirms device-dependent parameters; when blinking red, this indicates the new values have not been verified. (c) The DM coefficients and max voltage specific to the DM used in the system.

To set/verify the values for the coefficients and maximum voltage one needs to look at the calibration plot delivered with the BMC DM. The calibration plots will look similar to the one shown in Figure 146, which has the axis of abscissas normalized to the maximum drive voltage for the DM. As can be seen in the graph, actuator deflection responds nonlinearly to drive voltage. For each plot, a 2nd order polynomial is fit to the peak displacement for two sets of displacement data. One represents the peak displacement when the same voltage is applied to a group of 4x4 actuators. The other represents the peak displacement when a voltage is applied to a single actuator. From the plot of displacement versus actual voltage, one uses the coefficients in the equation for the top trend line (4x4 actuators) to enter into the numeric boxes for coefficient A, B, and C.

Note: These values are unique to each DM; thus, they must be entered each time a new DM is introduced into the system. All values can be found on the "Deflection Curves" chart distributed with each DM (a sample chart is shown in Figure 146).

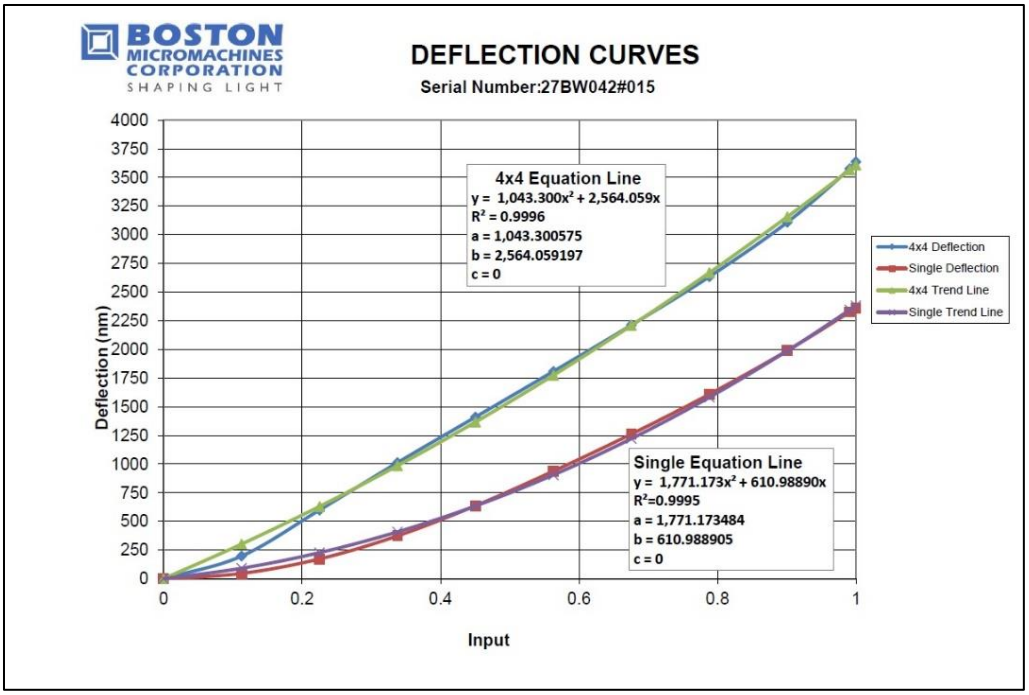


Figure 146 BMC Calibration Plot with Normalized Voltage

Deformable Mirror Settings

The **Deformable Mirror Settings** section of the tab controls various parameters that affect the deformable operation during calibration and closed-loop correction. See Figure 147.

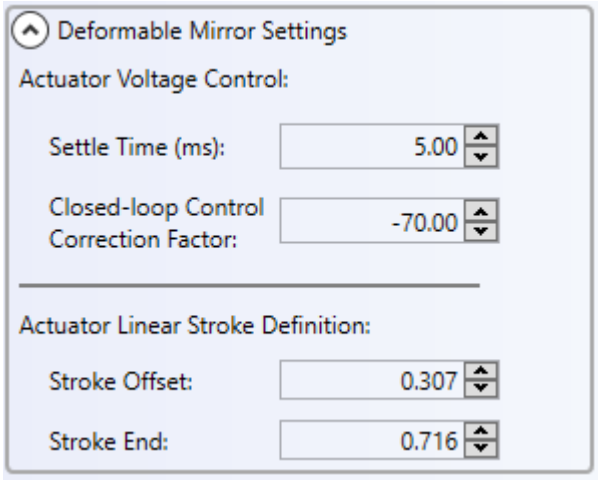


Figure 147 Deformable Mirror Settings Section of BMC DM Controller Tab

Actuator Voltage Control

- **Settling Time** - This is the time, in milliseconds, for a BMC DM to wait after mirror voltages have been applied.

- **Closed-loop Control Correction Factor** - This is a feedback control loop gain factor. It governs the magnitude of the deformable mirror correction adjustment. Larger negative values will make larger correction adjustments than smaller negative values.

Actuator Linear Stroke Definition - Piezoelectric actuators are non-linear, as may be seen in Figure 146. During the calibration process one wants to operate the DM within the linear portion of the deflection versus voltage response curve. To achieve this, the parameter **Stroke Offset** and **Stroke End** are included during the calibration process.

- **Stroke Offset** - This is the relative voltage (normalized to the max operating voltage). A safe value for this is 0.3 (30% of the max drive voltage). This indicates the voltage that all actuators will be set at the beginning of the calibration process.

- **Stroke End** - This is the relative voltage that each actuator will be poked to during the calibration process. A safe value for this parameter is 0.7 (70% of the max drive voltage).

Display and Output

Data Display - This option offers control over whether to display the graphic data window. For the BMC DM family of mirrors there is one data display option, the **BMC Actuator Values**. The values may be selected to be displacement in nanometers or the voltage control signal, an integer bit value. Checking this data output option will make the data window visible. Unchecking this option will close the data window.

Signal Output - BMC Actuator Displacements is the signal for BMC family of deformable mirrors used in closed-loop control. Checking this signal output option will save the values of the BMC actuator displacements into a file when the system is in recording mode.

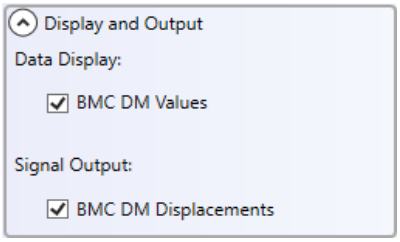


Figure 148 Display and Output Section of BMC DM Controller Tab

8.2.5.2. BMC DM Controller Element Data Display

A surface graph is used to display the BMC DM Values data. Please refer to **Wavefront Data Display Window** in Section 8.2.2.2.1 on how to alter the surface plot.

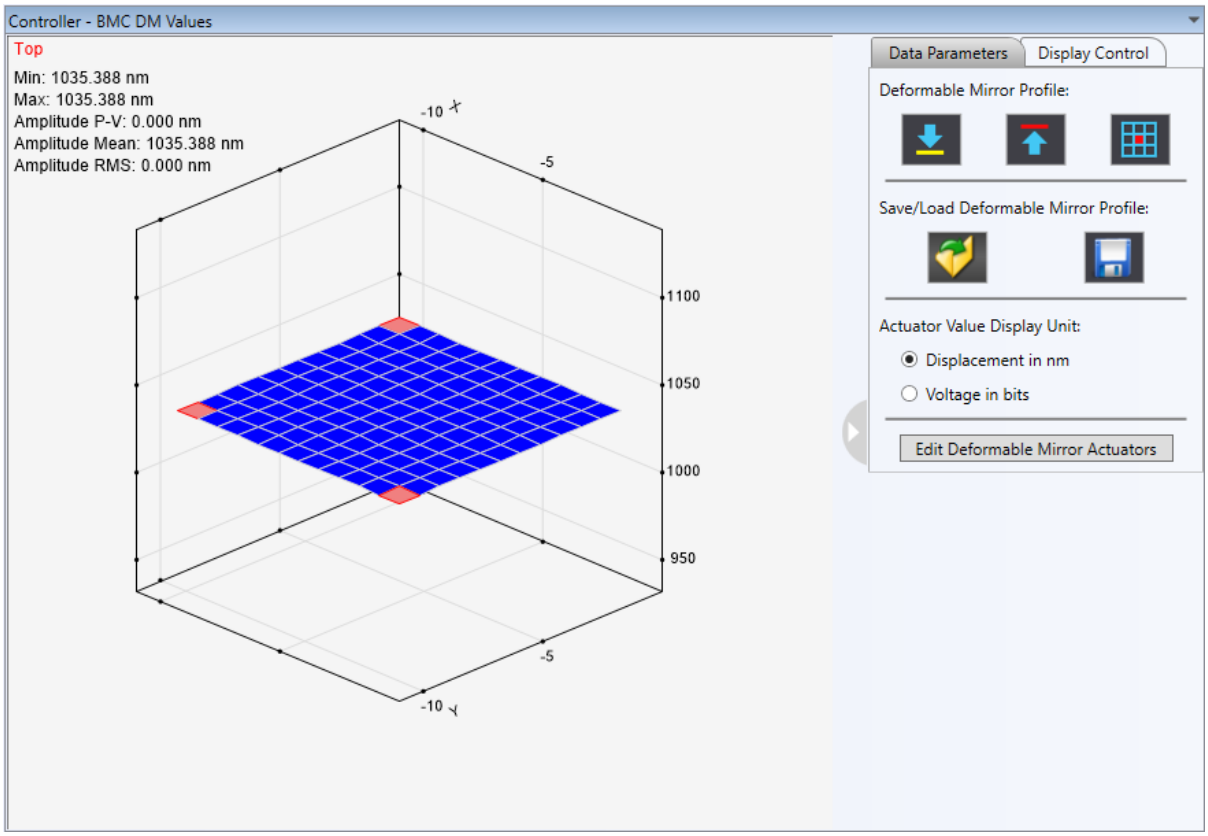


Figure 149 BMC DM Values Display Window

Data Parameters Tab

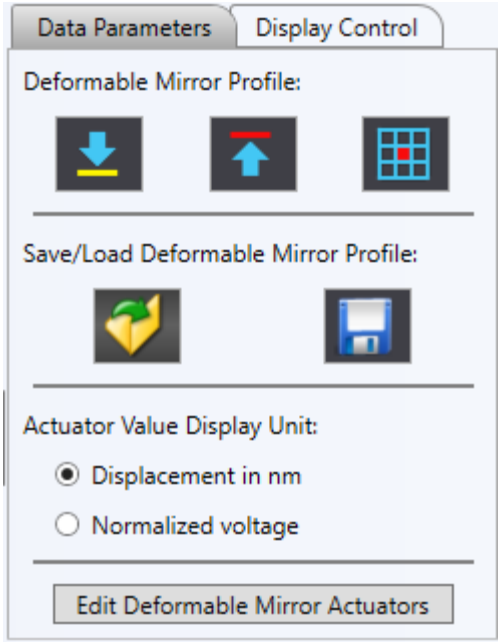


Figure 150 Data Parameters Tab Within the BMC DM Graphic Data Window

Deformable Mirror Profile Control

Table 6 explains the functionality of the mirror profile control buttons.

Icon	Description
	Clicking this icon sets all the mirror actuator voltages to the user defined stroke offset (minimum) displacement.
	Clicking this icon sets all the mirror actuator voltages to the user defined stroke end (maximum) displacement.
	Clicking this icon sets all but the center four (4) actuators to the maximum user defined stroke end (minimum) displacement, and the center four (4) actuators to the user defined stroke offset (minimum) displacement.

Table 6 Data Parameters Icons and Description of Functionality for the BMC DM Graphic Data Window

Save/Load Deformable Mirror Profile

Icon	Description
	Clicking this icon opens a standard file open window for one to open an xml formatted file.
	Clicking this icon saves the current actuator voltages to an xml formatted file.

Table 7 Save/Load Deformable Mirror Profile

Deformable Mirror Profile File Format

The segment values are saved to and read from a data file in XML format. An example of a file (beginning and end) is shown below. After the declaration lines, the data starts with an element named **NumActuators**, which indicates the total number of actuators. For the case of the BMC deformable mirror there are 144 actuators. After this line in the file there is a repeated series of elements named **DMValue**, with sub-elements **Index** and **Value**, which indicate the segment number and set value, respectively, for each actuator.

```
<?xml version="1.0" encoding="utf-8"?>
<DMVoltageProfile xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:xsd="http://www.w3.org/2001/XMLSchema">
  <NumActuators>144</NumActuators>
  <DeformableMirrorVoltageProfle>
    <DMValue>
      <Index>0</Index>
      <Value>1449.43551</Value>
    </DMValue>
    <DMValue>
      <Index>1</Index>
      <Value>1059.43551</Value>
    </DMValue>
    <DMValue>
      <Index>2</Index>
      <Value>1059.43551</Value>
    </DMValue>
    <DMValue>
      <Index>3</Index>
      <Value>1059.43551</Value>
    </DMValue>
       *
       *
       *
    <DMValue>
      <Index>140</Index>
      <Value>1059.43551</Value>
    </DMValue>
    <DMValue>
      <Index>141</Index>
      <Value>1059.43551</Value>
    </DMValue>
    <DMValue>
      <Index>142</Index>
      <Value>1059.43551</Value>
    </DMValue>
    <DMValue>
      <Index>143</Index>
      <Value>1059.43551</Value>
    </DMValue>
  </DeformableMirrorVoltageProfle>
</DMVoltageProfile>
```

Actuator Value Display Unit

The graphical display of the DM actuator voltages may be set to have units of displacement (in nm) or normalized voltage, which is ranged from 0 to 1. The control signals to the DM control box are integer bit values. Internal to BMC's DM control box, there is a maximum DM control voltage of 300 V. A 14-bit D-to-A controller is used such that 0 represents 0 V and 1 represents 300 V. Each controller is matched to the DM it ships with, and has a maximum output voltage limit set to the maximum control voltage allowed to the DM.

Note: The DMs are not warrantied against damage caused by operating them above their documented maximum voltage. It is important to only use the control box/deformable mirror combination that is shipped together.

Edit Deformable Mirror Actuators

Checking this box will pop up a window with controls that allow the user to manually adjust the voltages to mirror actuators. See Figure 151.

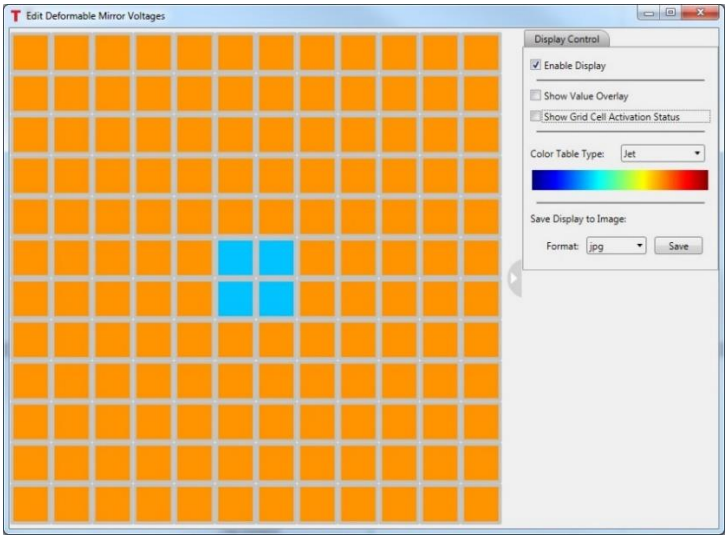


Figure 151 Window with Controls to Vary / Set BMC Multi DM Mirror Actuator Voltages

The left side of the window includes an NxN array of squares (For BMC Multi DM, N = 12; For BMC Mini DM, N = 6), each representative of an actuator. At the right side of the window there is a tab titled Display Control, which includes options for affecting the graphic actuator array.

Hovering the cursor over a segment will highlight the edge of the segment yellow and a small grey box will appear that displays the segment number and current segment displacement in unit specified by **Actuator Value Display Unit** (Figure 152). If the unit is Nanometer, the displacement in nanometers is dependent on the DM coefficients entered in the Device-dependent Settings section of the plugin controller tab (see section **Device Dependent Settings** for more information).



Figure 152 Hovering over a segment highlights the edges yellow and displays a box containing the segment number and displacement in microns.

When one clicks into a segment the segment perimeter will turn red, as shown in Figure 153. Additionally, when one right-clicks into a segment a grey rectangle window will pop up next the segment that includes a numeric control and a horizontal slide control, see Figure 153. The value of the segment may be varied by entering a new value into the numeric box, clicking the up/down arrows at the right side of the numeric box, or by grabbing the slide with the cursor and sliding it right/left. The color of the segment will change based on the color table type selected. See Figure 154.

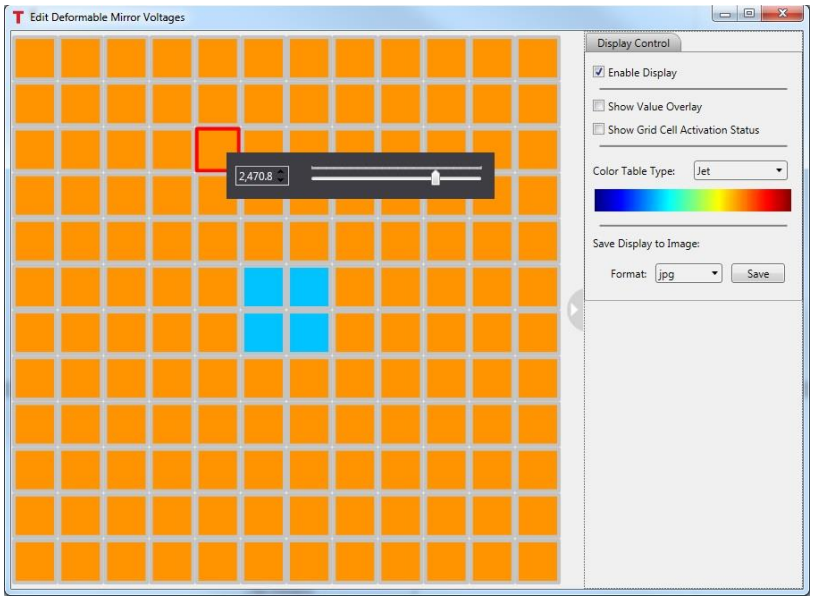


Figure 153 Clicking in a segment highlights the edges red. Right clicking in a segment brings up a control box to change the value of the segment/actuator.

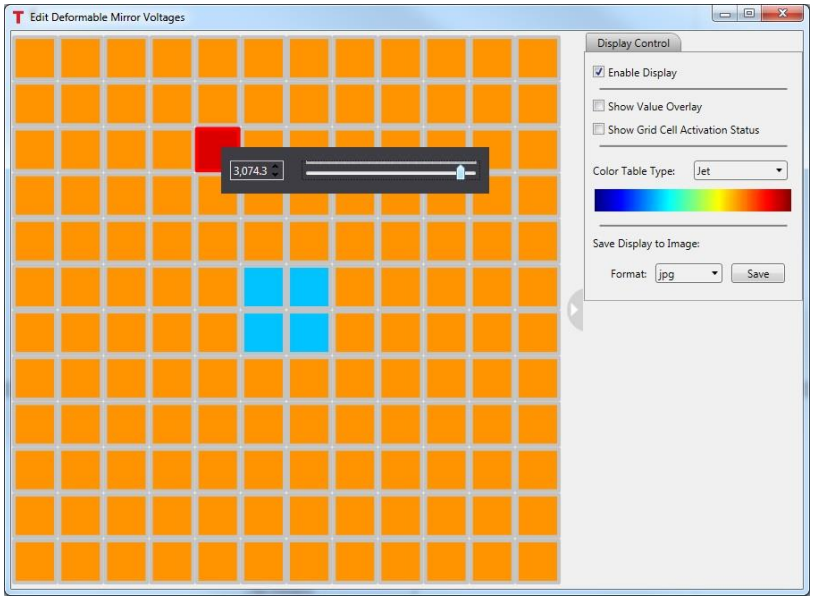


Figure 154 The color of the segment changes based on the set value and the color table selected.

Enable Display - Checking the box enables display updating. With it unchecked, the actuator display will not be updated as applied voltages are changed. If one clicks into segment and changes the voltages manually, they will affect the mirror actuators.

Show Value Overlay - Checking this checkbox will display the current value for each actuator within the respective display segment. See Figure 155.



Figure 155 Checking the box labeled Show Value Overlay will display the current segment values inside each segment.

Show Grid Cell Activation Status - Checking this checkbox will display small grey checkboxes in the upper right corner of each segment (Figure 156). If the box is checked, the segment / actuator is active, meaning that during closed loop control the value of the actuator is controlled directly. If not, the actuator is inactive, and the value of the actuator is calculated to follow its nearest neighbor actuators' values.

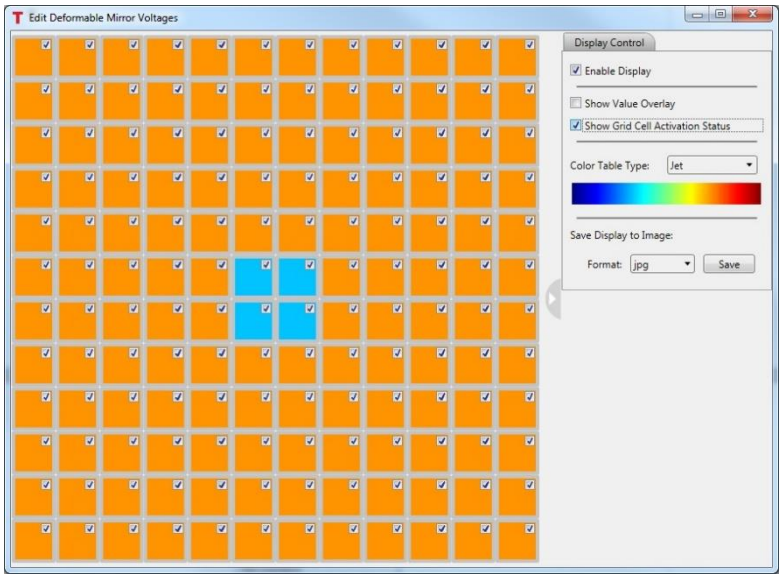


Figure 156 Checking the box titled Show Grid Cell Activation Status will display small box in the upper right corner of each segment. Checked indicates active. Unchecked indicates inactive.

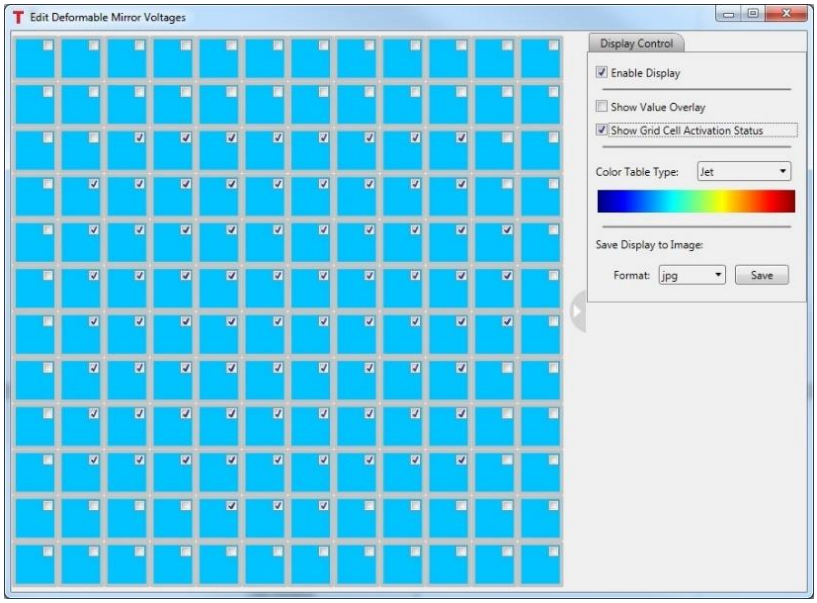


Figure 157 Mirror voltage window after calibration. All segments set at offset (min) value and actuators determined to have low influence are set as inactive (unchecked).

During the calibration process, the activation status of each actuator is determined based on the influence it has on affecting the measured wavefront. Actuators deemed to have low influence are set inactive. Figure 157 shows the result of a calibration on the mirror voltage window. Note in the figure that all the actuator values are set to the same value and the inactive actuator segments do not have checks in the activation status boxes.

Color Table Type - The dropdown menu shown in Figure 158 shows the seven (7) color schemes available for representing the DM mirror segment values.

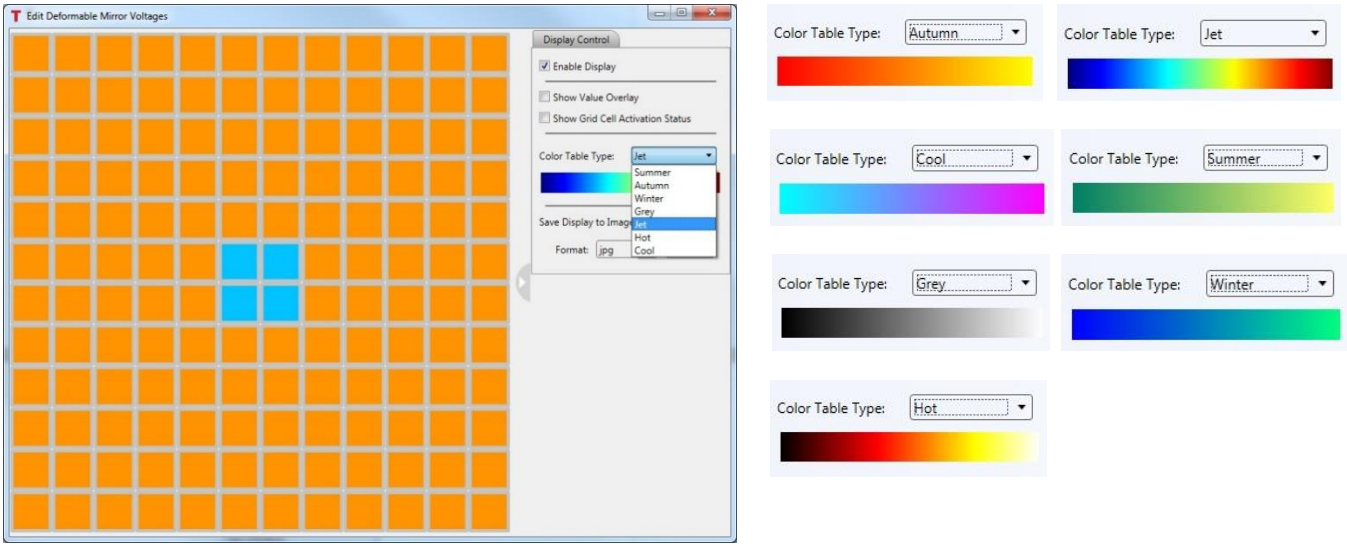


Figure 158 Color table options display in a dropdown menu, and the color bars for each option.

Save Display to Image - At the bottom of the Display Control tab there is a dropdown box labeled Format. Select the format in which to save the image. The available options are jpg, bmp, tif and png. After selecting the image format, click the save button to the right of the dropdown selection box. A standard save file window will open, with the default file location,

C:\Users\<windows_username>\Documents\Thorlabs\ThorAOControl\[UserProfile_Name]\[ControlGroup_Name]\[ControlSystem_Name]

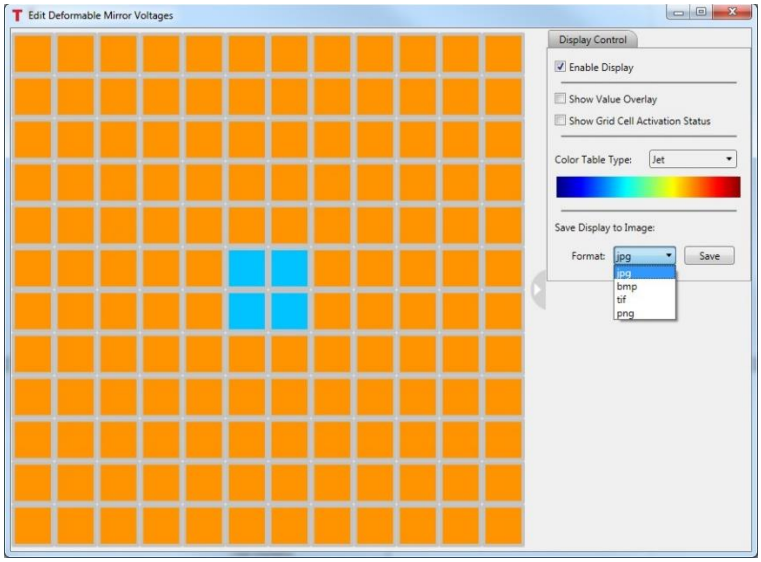


Figure 159 The segment display section of the window may be saved in various image formats. Available image options are displayed in dropdown menu.

Display Control Tab

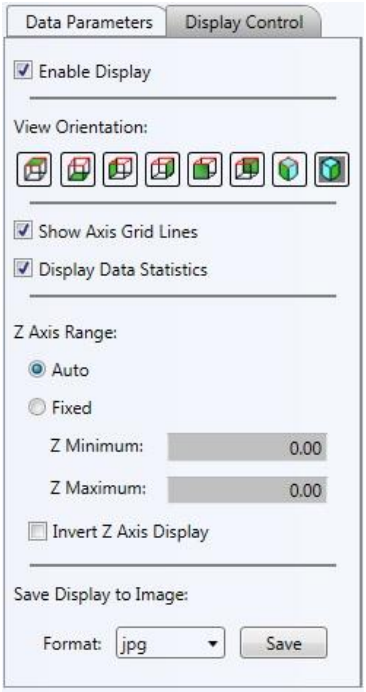


Figure 160 Display Control tab includes controls to tailor the graphic display.

Enable Display - Checking this box enable the display to be updated anytime the voltage map to the DM has changed. With it unchecked, the display will not update in close-loop control mode, or when actuator values are changed manually.

View Orientation - These controls rotate the graphic display to view from the top, bottom, right, left, front, back, elevated from the top right, and elevated from the top left.

Show Axis Grid Lines - Checking this box will add gridlines to the XY, XZ and YZ coordinate planes of the graphic display. See Figure 161.

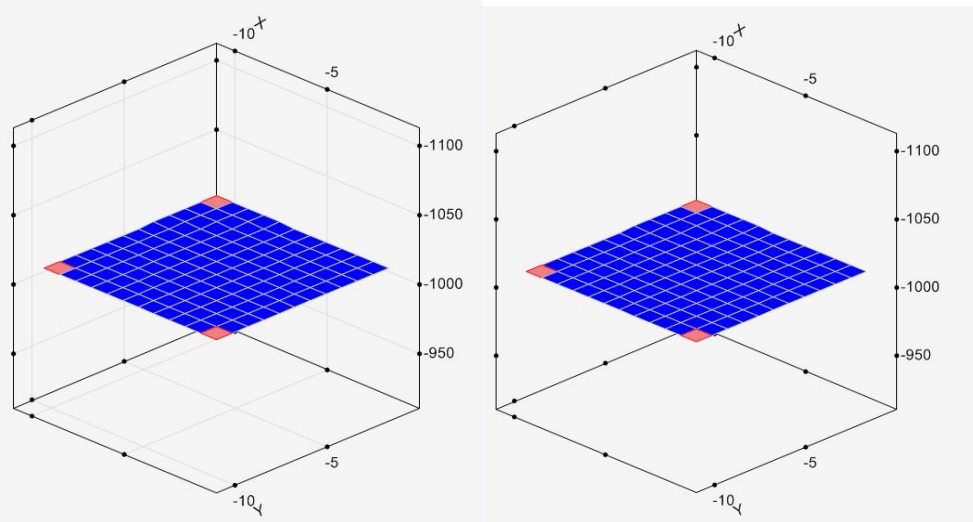


Figure 161 Actuator voltage graphic display with (left) and without (right) gridlines.

Display Data Statistics - Checking this box sets the statistics of the DM actuator values to be displayed in the upper left corner of the graphic data window. See Figure 162.

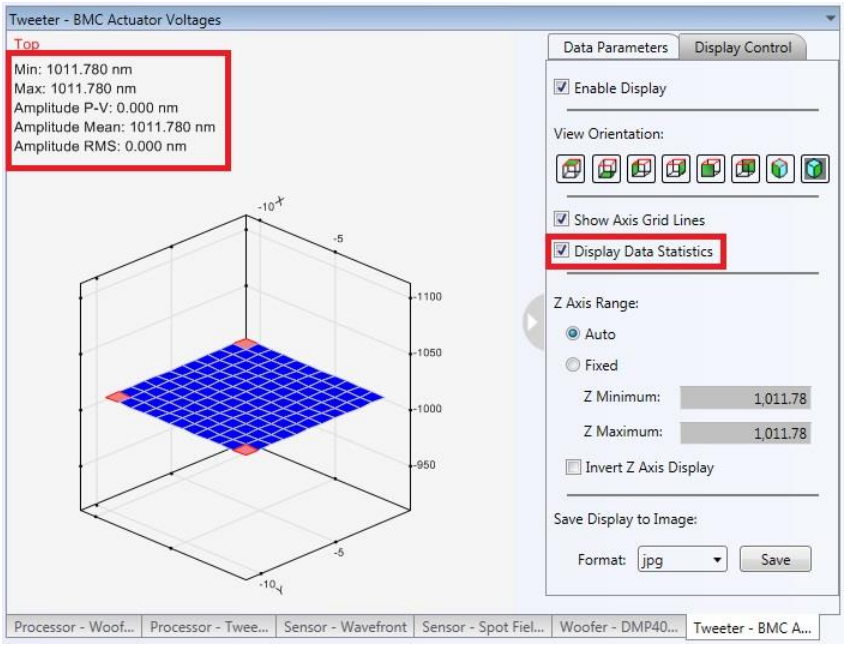


Figure 162 Display Data Statistics checkbox sets whether the statistics displayed in the upper left red box is displayed.

Z Axis Range - The graph of the set actuators' displacements plots the displacement of each actuator along the z-axis with the actuator positions arranged in the x-y plane. The range of the z-axis may be set to auto-scale by checking the radio button. If the Fixed radio button is checked, the user may enter the minimum and maximum z-values for the z-range using the numeric control boxes.

Additionally, the checkbox labeled Invert Z Axis Display may be checked to flip the z-axis orientation. Some users will prefer one orientation versus the other. As actuator displacement / voltages are increased the physical mirror surface location is pulled downward. Inverting the z-axis will invert the sign of the displacement to represent displacements as negative/downward displacements.

Save Display to Image options - The displayed graphical image of the segment and arms may be saved in four different image formats, jpg, bmp, tif or png. Figure 163 shows the dropdown menu used to select the format. Clicking the Save button will pop up a window to select the folder location and filename.

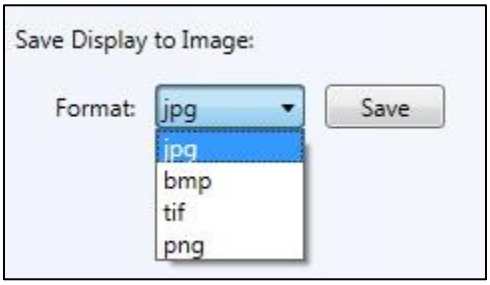


Figure 163 Options for saving image of graphic display.

Chapter 9 The AO Kit Final Alignment and Calibration

9.1. Adaptive Optics Kits with Thorlabs DMH40 or DMP40 Deformable Mirror

The following steps help to fine tune the alignment and calibrate the AO Kit system. These steps pick up after the steps covered in Section 4.8 on page 22.

Step 1. Align the center of the DM to the center of the SH sensor.

1) With the WFS, and DM, connected to the computer, start the AO Kit application, and make sure the Shack-Hartmann window is showing.

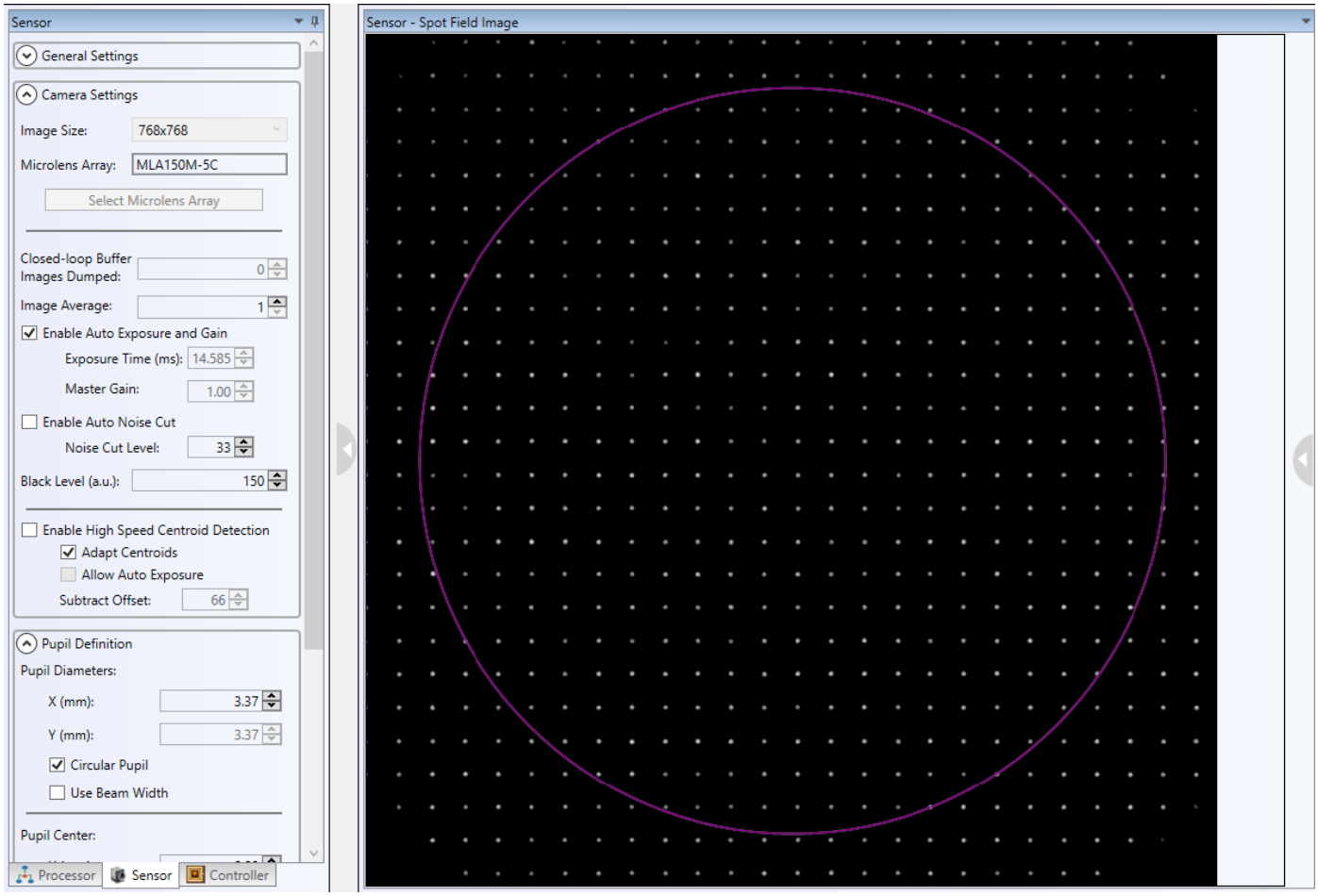


Figure 164 Spot Field created when the incident beam is properly centered on the WFS.

2) The pupil diameter can be set large enough to facilitate centering the pupil to the DM projection on the WFS. Note, the WFS is rotated 90° with respect to the plane of the system; therefore, the T-B (top-bottom) direction is the L-R direction on the DM. The width of the DM projection on the WFS in this direction is smaller than the T-B dimension due to the angular alignment of the DM relative to the subassembly-3 and WFS optical path. See Figure 169. Note the diameter 3.88 mm in the figure. This value was used to calculate the pupil diameter at the WFS for a single DM AO Kit including the DMP40 that is equivalent to the 10 mm active diameter at the DM, 3.37 mm as seen in the preceding figure. 3.88 mm * (10 mm / 11.5 mm) = 3.37 mm.

Step 2. Shack-Hartmann sensor fine-alignment.

Clicking the Wavefront tab to show the measured wave front, and make sure the Cancel Tilt check box is unchecked. One may see a measured wave front similar to that shown in Figure 165. This average tilt evident in the figure needs to be removed before calibrating the system. To do so, adjust the tip / tilt controls on the WFS mounting platform until the average tip/tilt is removed. The resulting wave front may look like that in Figure 166. After achieving this, check the spot field tab and adjust the x- and y-position of the WFS until the spot field is nominally centered. Then check the wave front tab. This process may need to be repeated until the average tip/tilt is removed and the spot field is centered. Check and uncheck the Cancel Tilt checkbox until the difference between the displayed wavefronts with the box check and uncheck are barely distinguishable.

After the WFS angle and position is set, open the spot field tab, center the pupil on the spot field and make sure the pupil diameter is set to the value representative of the 10 mm active DM diameter.

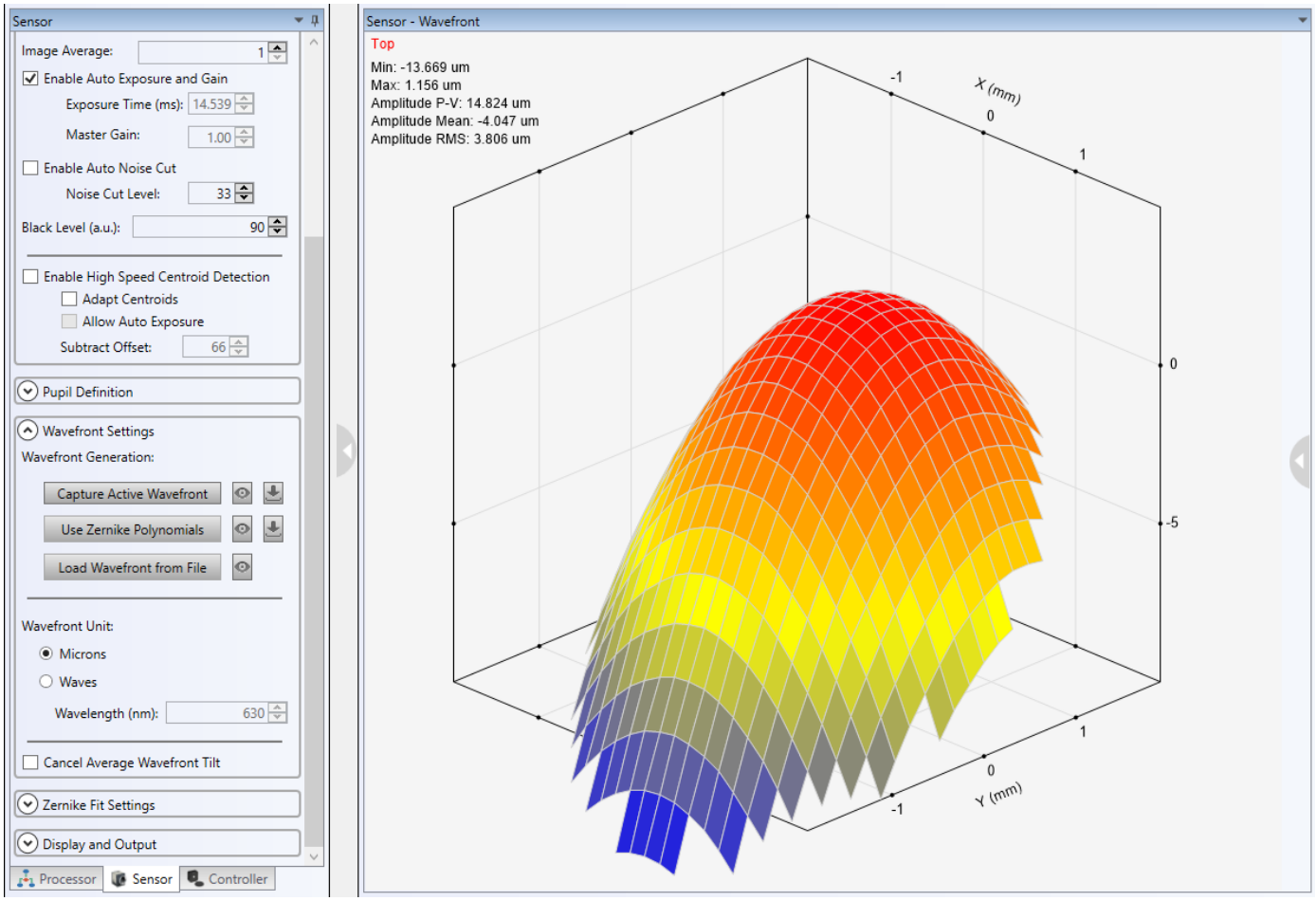


Figure 165 Sample of measured wavefront with slight average tilt.

After adjusting

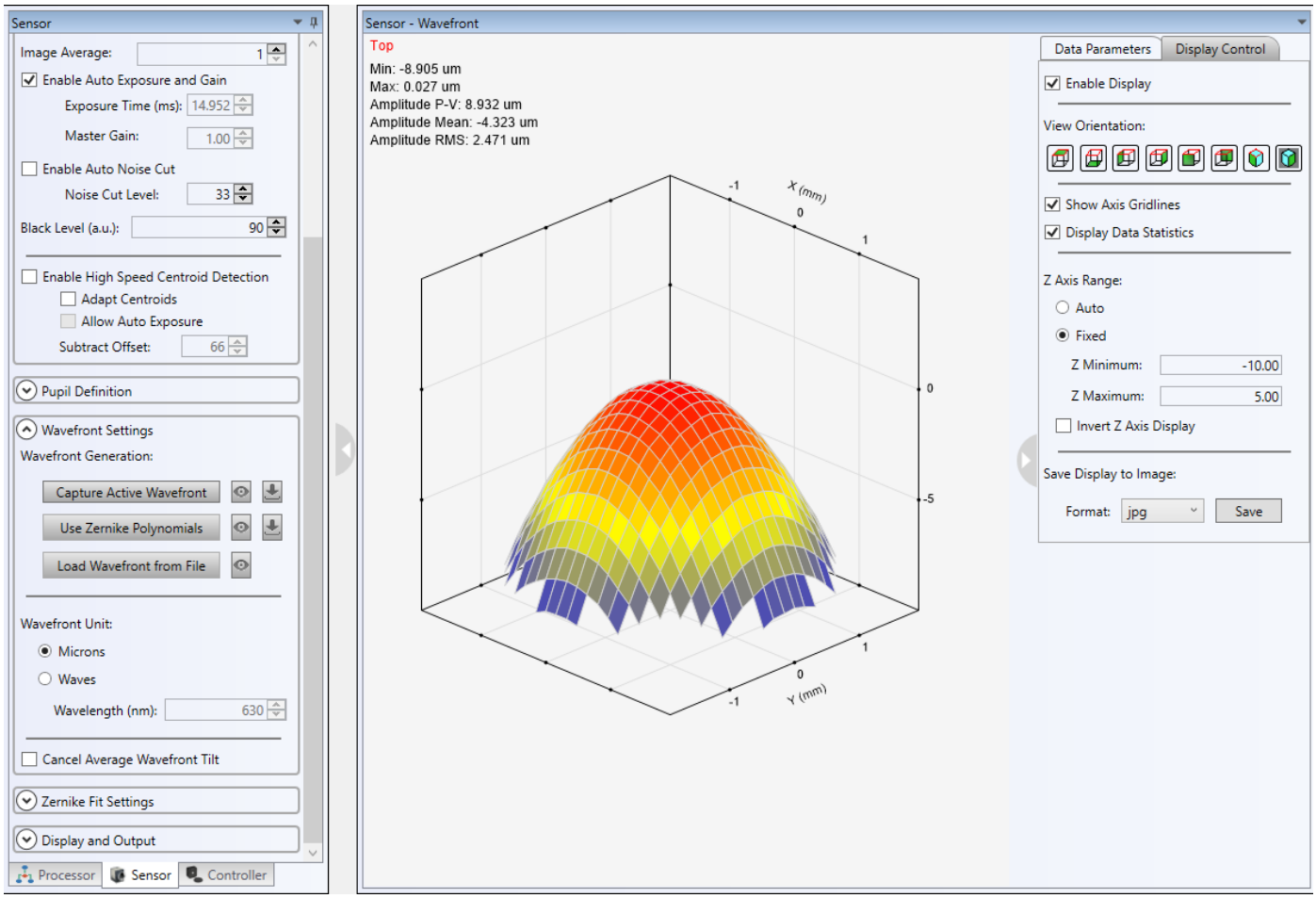


Figure 166 Sample of measured wavefront with tilt corrected and centered.

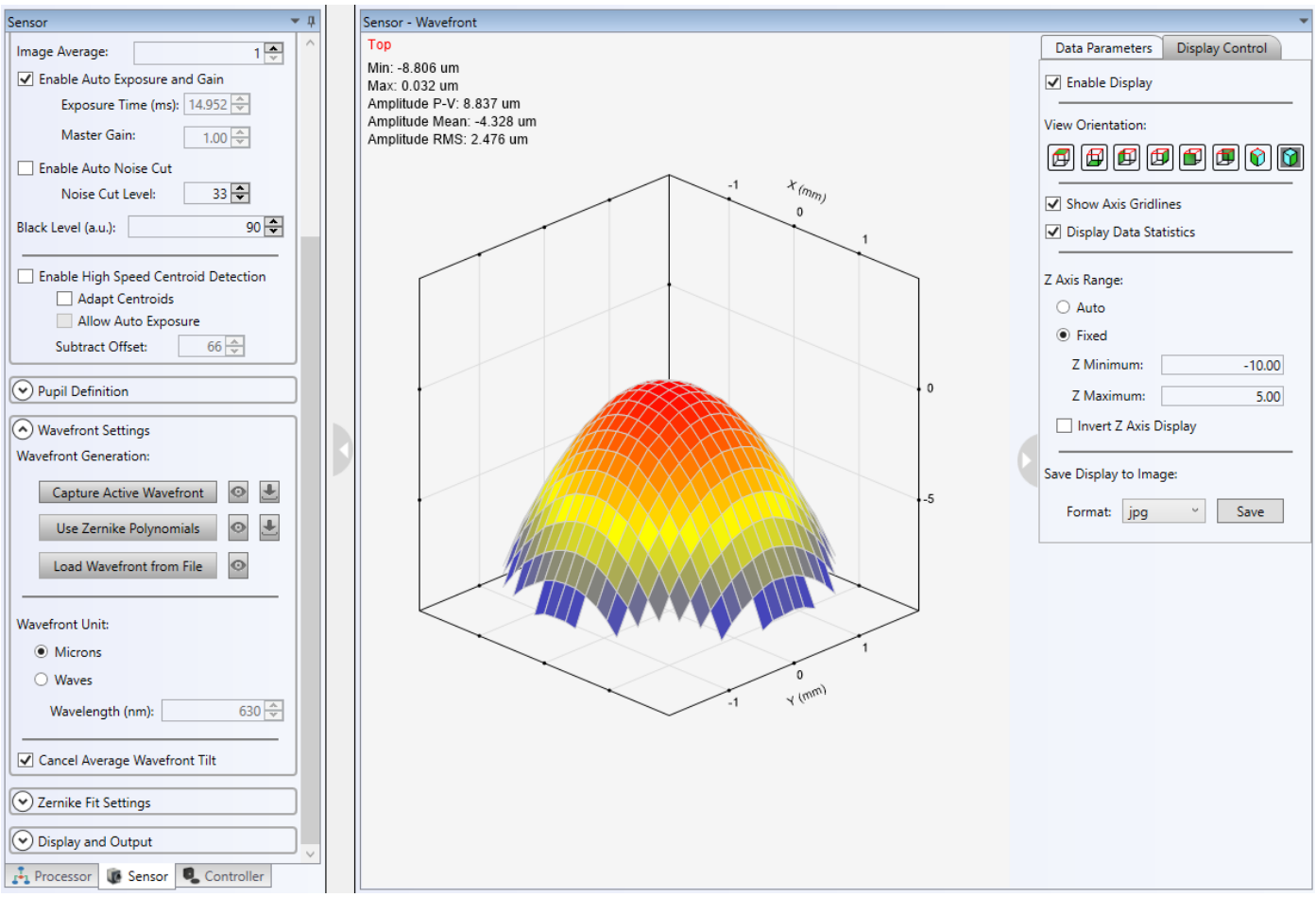


Figure 167 Sample of measured wavefront with tilt corrected and centered with Cancel Tilt un-checked.

Step 3. The system is now ready for the Deformable Mirror calibration.

1) Initiate the calibration by clicking the button from the toolbar.

2) After initiating the calibration, the user will see the calibration process displayed in Figure 168.

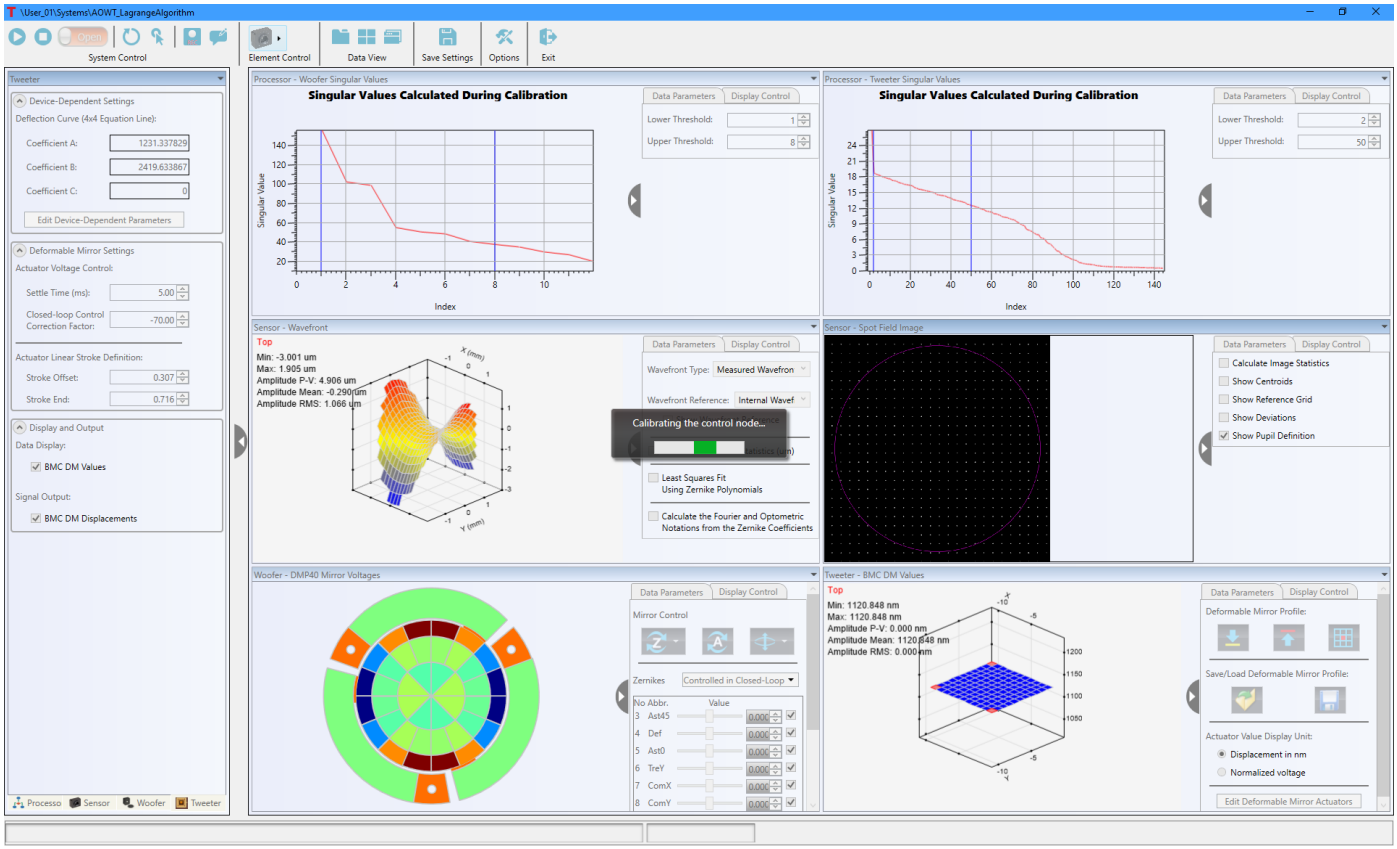


Figure 168 AOWT_LagrangeAlgorithm Calibration Process

9.2. Adaptive Optics Kits with BMC Deformable Mirror and the Woofer-Tweeter AO Kit

After assembling the optomechanical system and installing the software, a final alignment procedure must be performed prior to calibrating the system for adaptive control. The following are the alignment objectives:

1. The center of the laser spot through the sample region should be imaged to the center of the BMC deformable mirror.
2. The center of the DM should be aligned to the center of the Shack-Hartmann sensor. The active area of the DM (4.4 mm x 4.4 mm) is imaged onto the lens array of the SH sensor via a 1:1 optical relay. Aligning the center of the DM with the center of the SH sensor ensures that the outlying DM actuators affect SH spot positions. The beam should then be centered in sensor array showing a spot field like the one below in Figure 169. Please note that the number of lenses available across the image will depend on the image size, which also impacts speed. The default image size is 768 x 768.

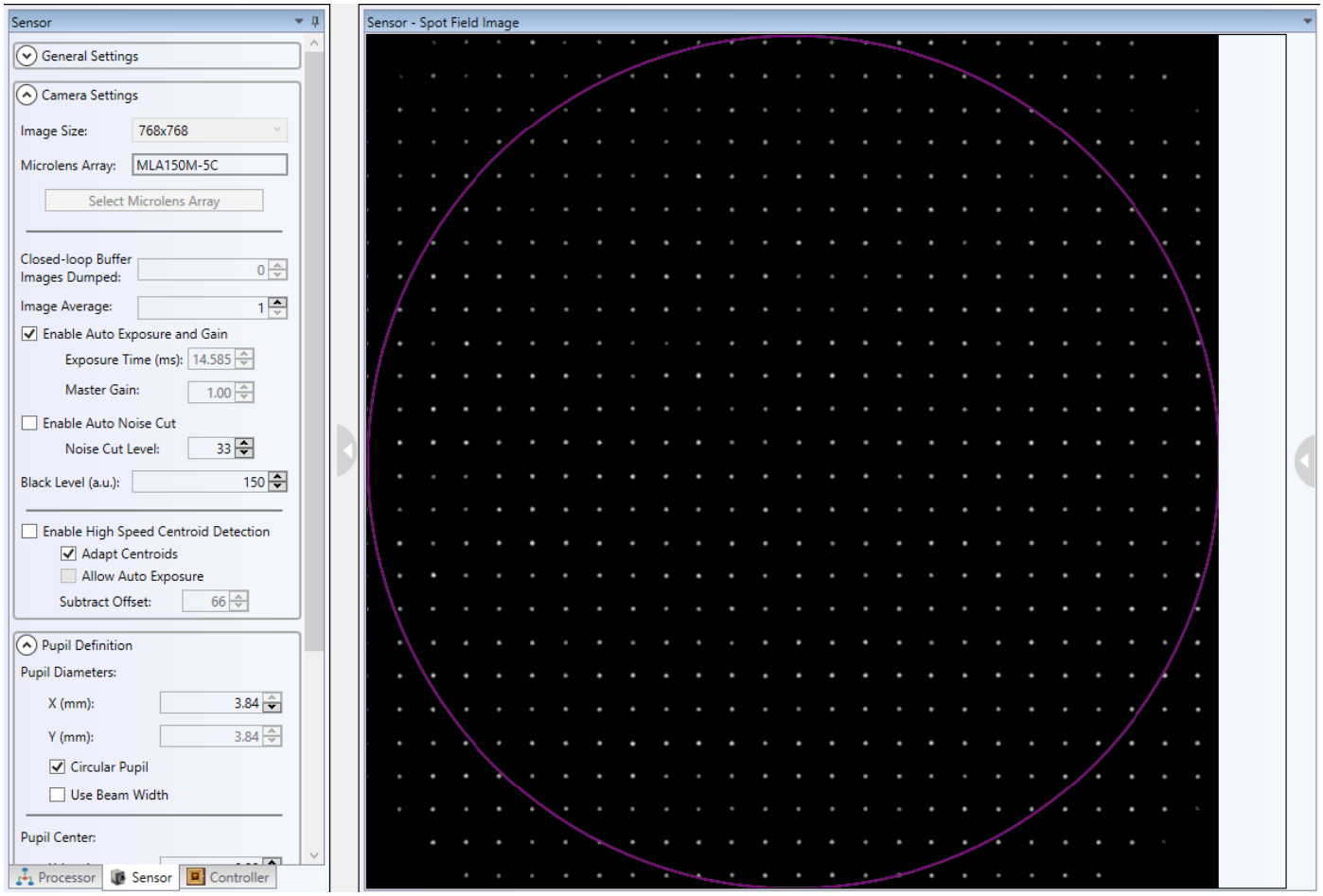


Figure 169 Spot Field created when the incident beam is properly centered on the WFS.

Step 1. Align the center of the DM with the optic axis of the input cage system, subassemblies 1 and 2.

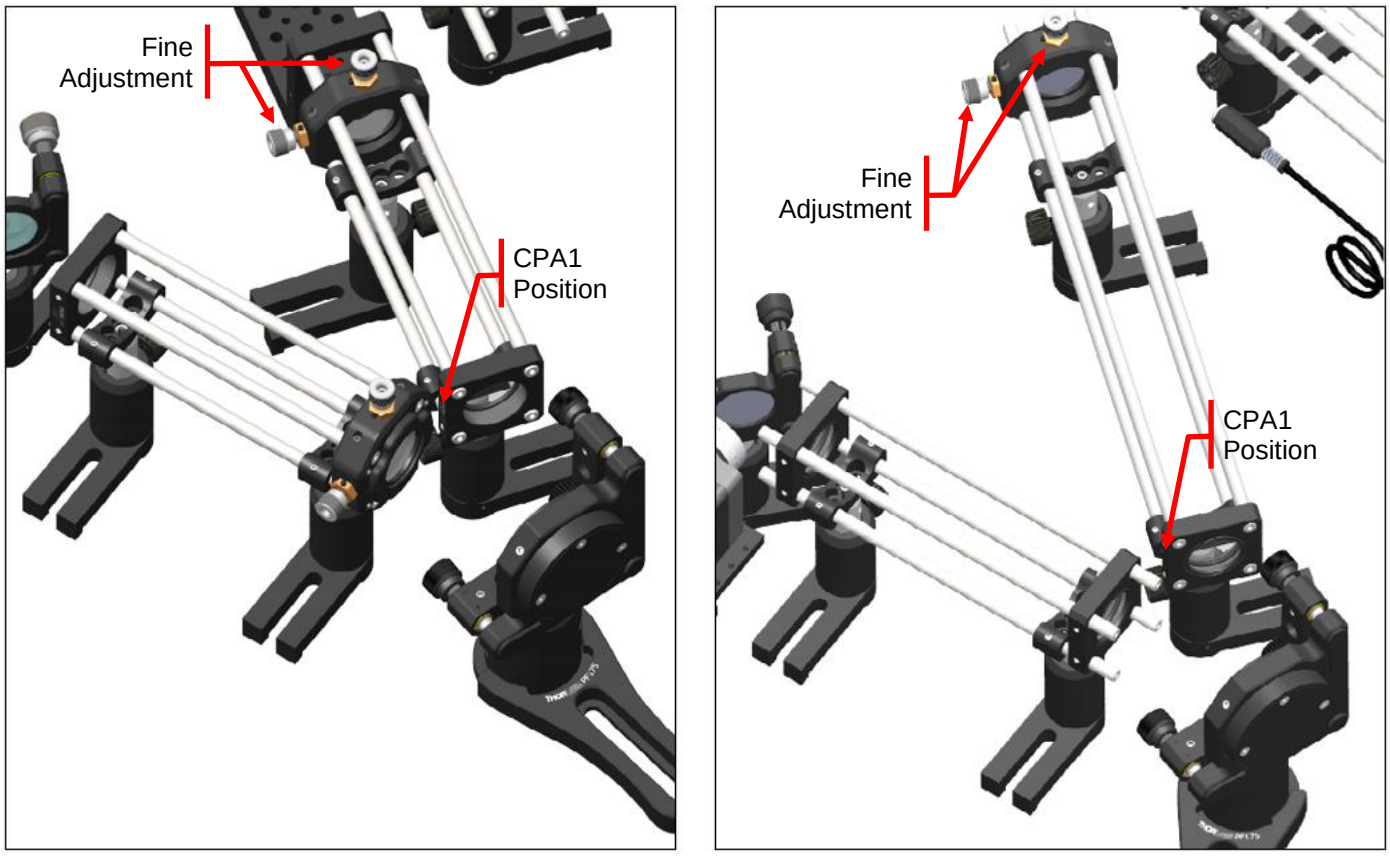


Figure 170 Aligning the center of the beam with the center of the DM140A. AOK5 relays shown left, AOKWT relays shown right.

1) Using the DM window of the AO Kit application (described in Section 8.2.5.2), set the four center actuator values between 3000 and 3500. This will pull a small group of center actuators and create a ‘dimple’ in the center of the DM.

2) With the laser diode module powered on, place a CPA1 cage system alignment plate onto the ER rods just prior to, or just after, the CBB1(/M) U-Bench that joins subassemblies 1 and 2 for AOK5 kits or just before the CXY1A of subassembly 4 of the AOKWT kits. The laser spot should be centered on the engraved target of the CPA1 such that there is a small visible spot incident on the BMC DM.

3) With the CPA1 set in position, adjust the vertical and horizontal position of the DM until the visible spot is centered in the dimpled region of the DM.

   a) While moving the DM, maintain its distance from the final lens of the input cage system.

   b) When the spot is close to the desired position, it may be more convenient to adjust the height of the TR posts and the positions of the UPH2 post holders that support the cage system to perform the final fine adjustments.

4) Set the DM values to ‘0’ (using the **Flatten** button in the DM window applies ‘0’ to all actuators) and manually adjust the yaw and pitch of the DM assembly until the beam reflecting from the DM into the final optical relay is close to propagating through the centers of the relay lenses. Although the fine alignment of the DM to the final optical relay section will be addressed in the following step, precise positioning of the DM at this point is very beneficial. Use a second CPA1 to check the alignment of the beam propagating through the optical relay.

Step 2. Align the center of the DM to the optic axis of the final optical relay section.

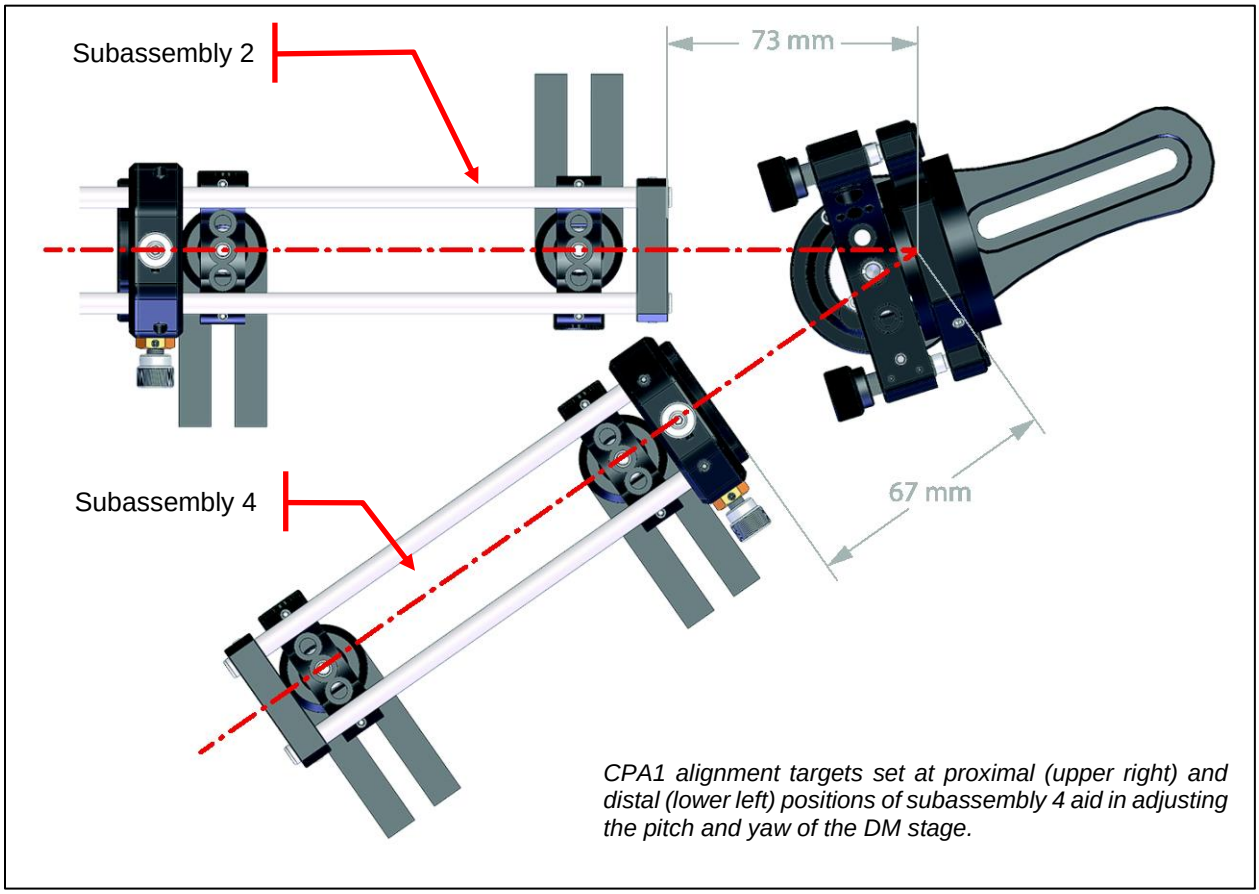


Figure 171 Aligning DM140A-35-Ux01 using the Cage System, AOK5 kit shown

1) With the DM mirror flattened (DM values set to '0'), place one CPA1 at the proximal lens (near the DM) and one CPA1 at the distal end of the final relay (subassembly 4 of an AOK5 kit or subassembly 6 of an AOKWT kit). Adjust the DM's pitch and yaw with the adjusters on the DM stage to center the beam entering the optical relay so that the spot passing through the first CPA1 is centered on the hole on the second CPA1 (refer to Figure 171).

2) If needed, the vertical and horizontal positions of the relay should be adjusted. For an AOK5 kit, center the CXY1A prior to making any vertical/horizontal adjustments to the relay.

3) Repeat steps 1 and 2 to center the beam through the final relay.

Step 3. Align the center of the DM to the center of the SH sensor.

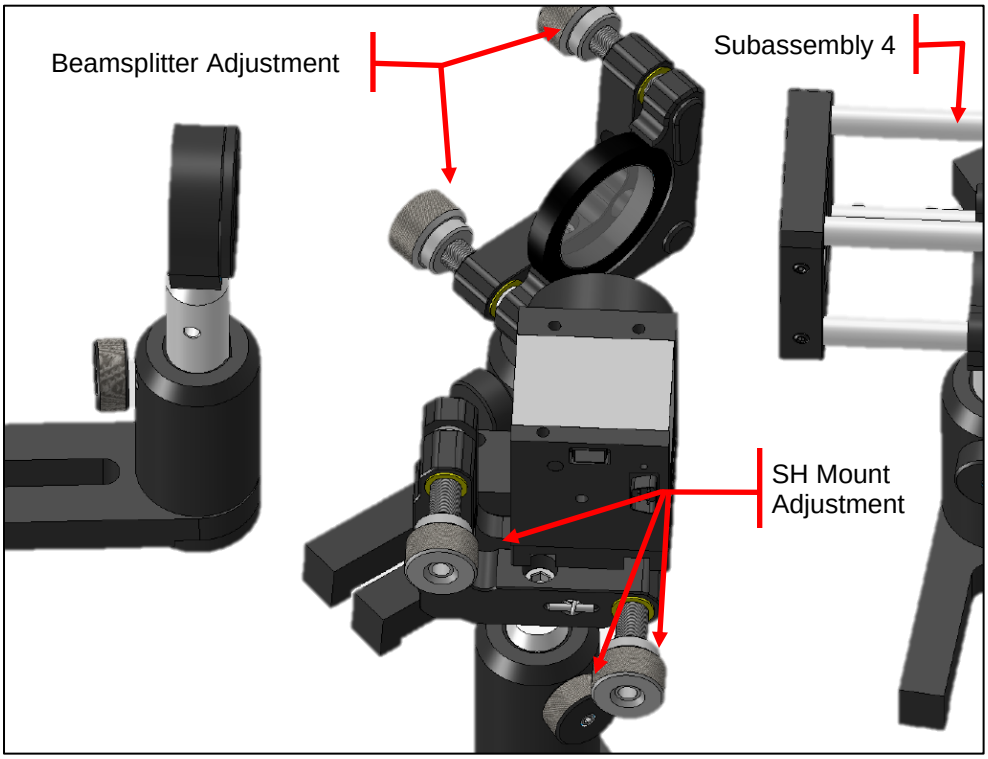


Figure 172 AOK5 SH Sensor Alignment Diagram

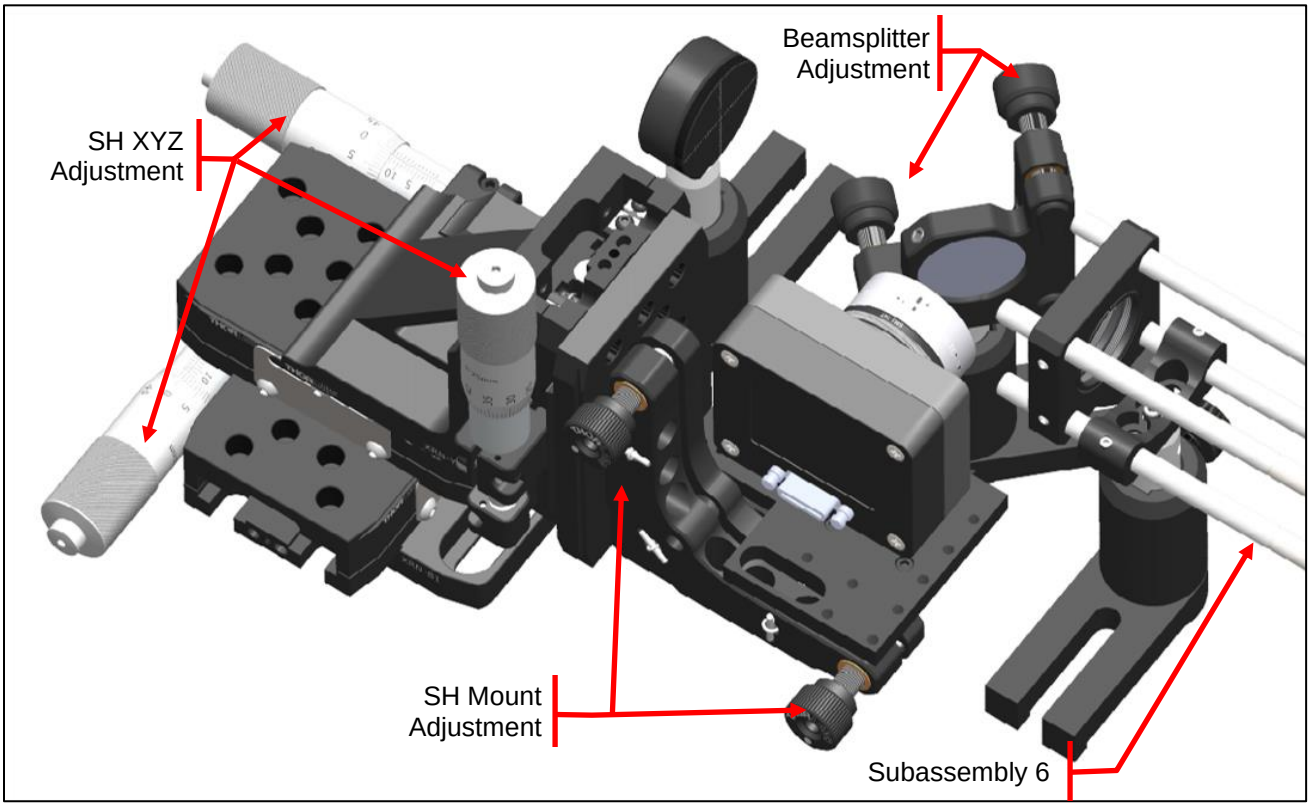


Figure 173 AOKWT SH Sensor Alignment Diagram

1) Ensure that the beam strikes the center of the beam splitter. If the beam is not centered, vertical alignment can be achieved by adjusting the height of the TR post and horizontal alignment can be achieved by moving the UPH2 itself. If only fine alignment is required, adjust the position of the beam using the knobs on the kinematic mount.

2) Adjust the SH sensor's position by following the same procedure used to align the beamsplitter. The AOK5 SH sensor position can be adjusted through movement of the TR post assembly and the AOKWT position adjusted using the XYZ stage. It may be helpful to screw the SM1A7 alignment disk onto the ND filter on the front of the wavefront sensor to provide a visual marker of the center.

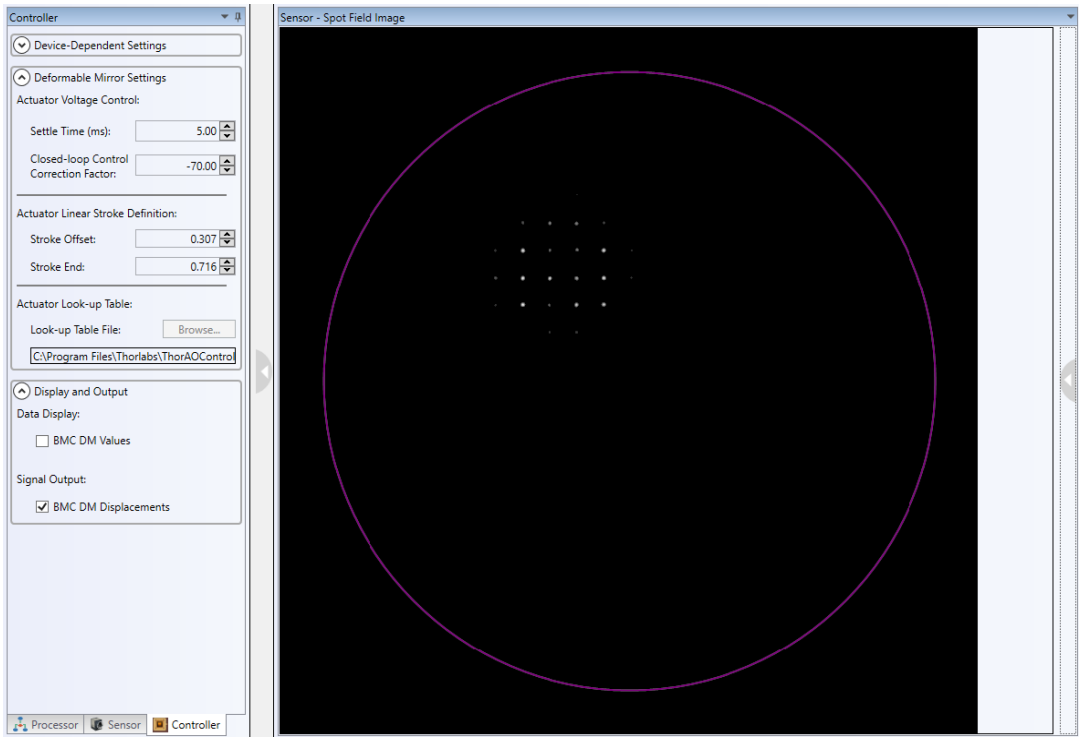
3) Adjust the spot distribution field of the SH such that the spots are centered on the spot field tab of the SH window. Figure 174 below shows how the spot distribution should be centered in the spot field tab screen.

    a) Adjust the height and position of the SH so that the beam goes through the center of the NE20A filter and onto the center of the SH's matrix.

    b) Once the field is relatively centered on the screen, use the kinematic adjustment for fine alignment of the beam (refer to Figure 172 or Figure 173 for knob adjustment information).

4) While monitoring the wavefront tab of the SH window (refer to Figure 174), adjust the pitch and yaw of the SH mount such that the wavefront flattens. The default setting for the wavefront display is auto-ranging, so the wavefront will never appear absolutely flat. However, with all CPA1's removed from the system, the peak-to-valley deviation of the wavefront should be less than 1 micron if things are aligned properly.

Spot Field Not Centered



Spot Field Centered

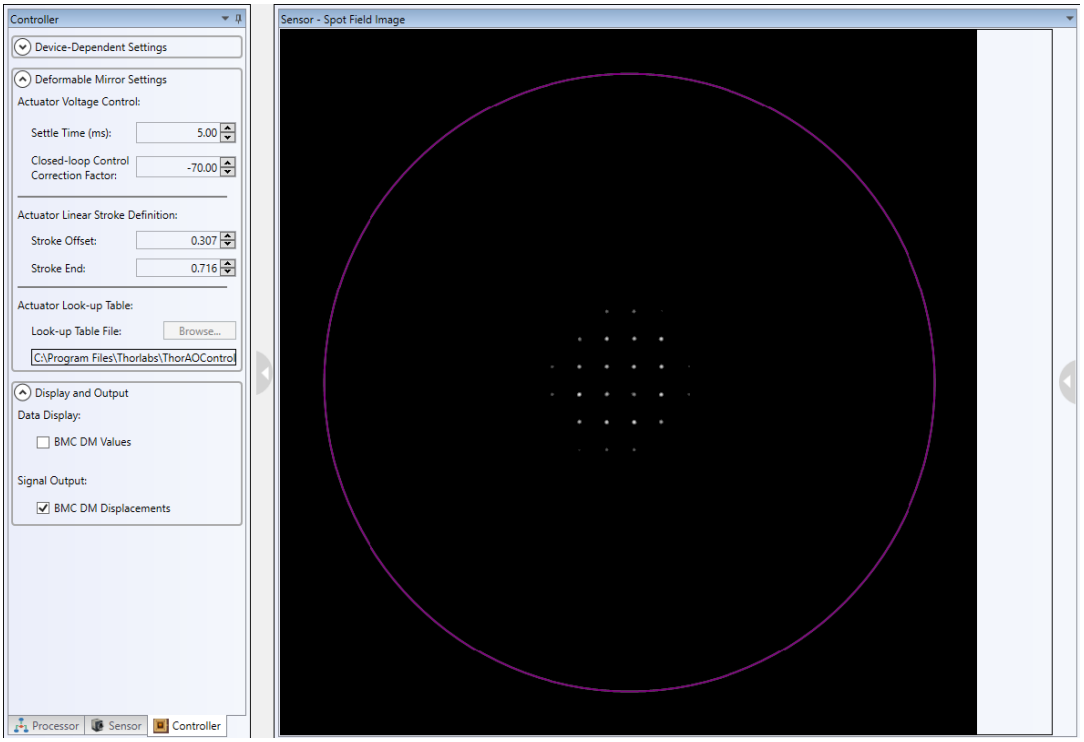


Figure 174 Spot Field Distribution Window

Step 4. Shack-Hartmann sensor fine-alignment: follow the steps in Section 9.1 to fine tune the Wavefront sensor.

IMPORTANT NOTE

The quality of the alignment can be judged by the amplitude value and the overall centricity of the beam on the SH matrix (as seen with the Spot Field Screen). A PV amplitude value from 0.2 to 1.0 signifies a good alignment. If good alignment cannot be achieved on the first try, repeat Steps 1 through 3 until good alignment is obtained.

Step 5. The system is now ready for the Deformable Mirror calibration.

1) Initiate the calibration by clicking the button from the toolbar.
2) After initiating the calibration, a spike should be seen on the DM surface, as displayed in Figure 175

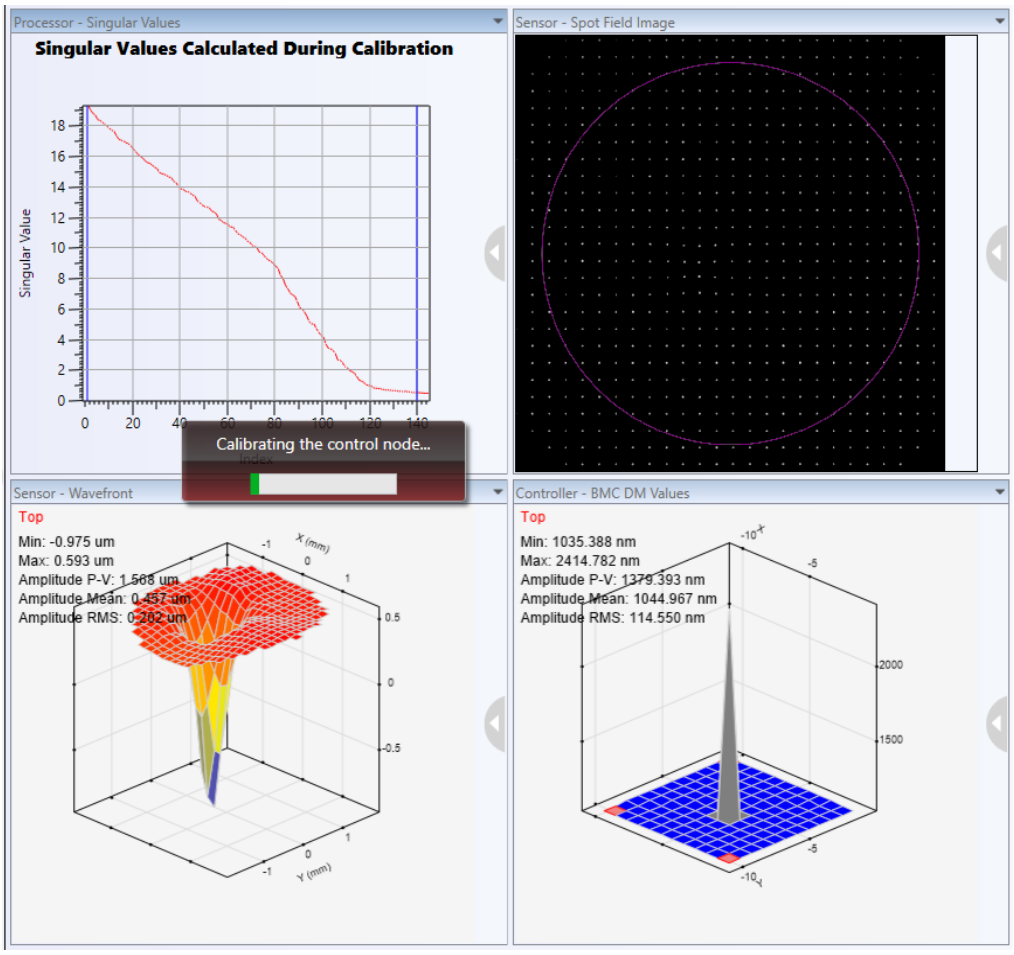


Figure 175 AOKit calibration process

3) A sample calibrated Deformable Mirror is shown in Figure 176. The system sets the effective Wavefront region (checked cells) and excludes marginal points that introduce noise (unchecked cells). A cell can be manually toggled between noise and verified status by checking it.

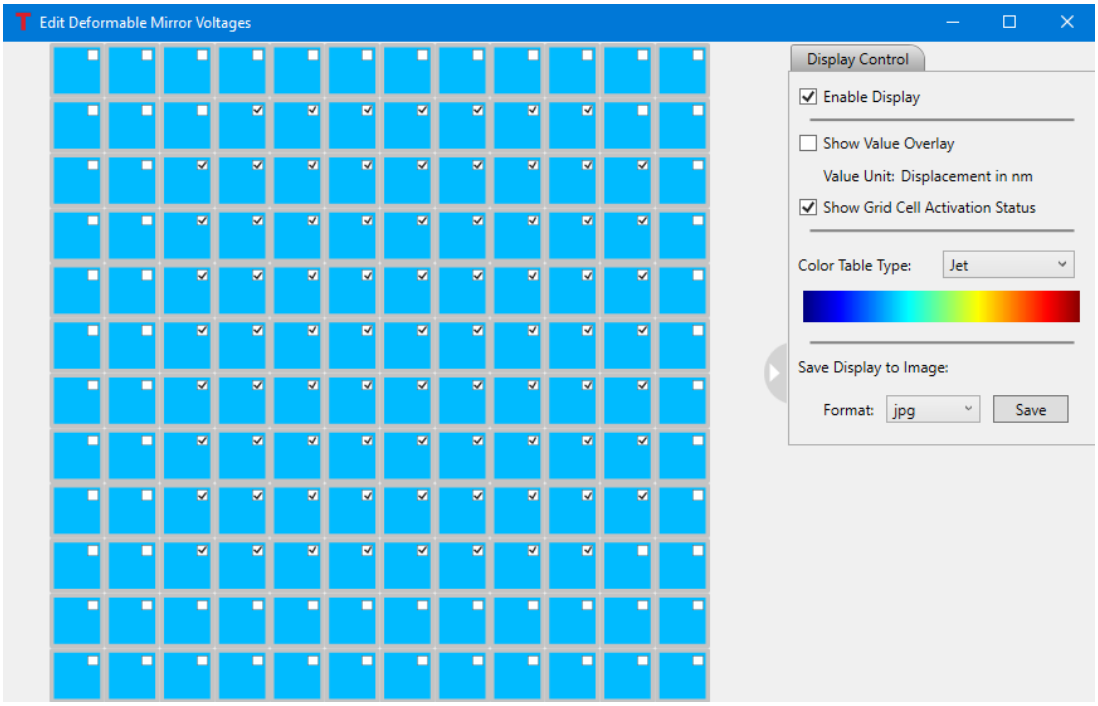


Figure 176 Calibrated DM with the Defined Effective Region (checked cells)

4) The system is now ready to be used in applications. Experimental samples may be placed into the CBB1(/M) mount midway between the CP33(/M) and CXY1A plates as shown below in Figure 177. Adjusting the singular values can greatly impact the performance of a system and the user should include adjustments to the ranges in optimizing a system. To start, for a BMC mirror try setting the Lower Threshold to 2 and the Upper Threshold to 55 and for the DMH/DMP start with a Lower Threshold of 1 and the Upper Threshold of 8.

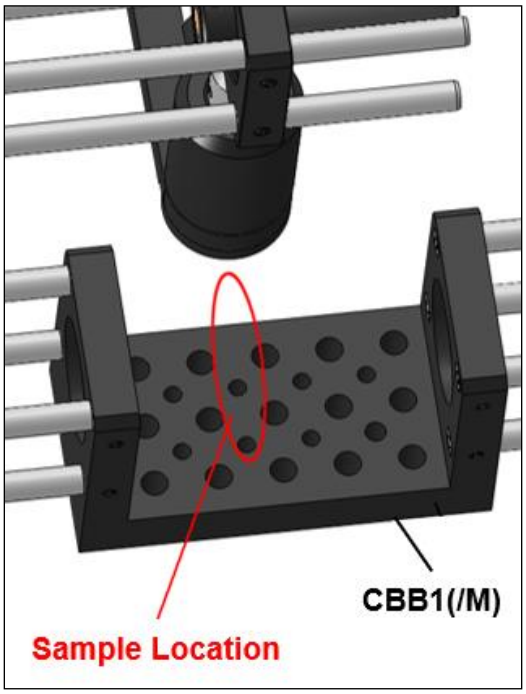


Figure 177 Sample Location

Chapter 10 Care of the AO Kit System

Handle the system components with care during transportation and unpacking. Banging or dropping the components can damage the system or decrease performance. Important precautions:

- Do not store or operate in a damp, closed environment.
- Do not store or operate on surfaces that are susceptible to vibrations.
- Do not expose to direct sunlight.
- Do not use solvents on or near the equipment.
- Keep away from dust, dirt, and air-born pollutants (including cigarette smoke).
- The system is not designed for outdoor use.
- Protect the equipment from rain, snow, and humidity.
- Do not expose to mechanical or thermal extremes.
- Protect the equipment from rapid variation in temperature.
- Handle all connectors, both electrical and optical, with care. Unnecessary force may damage the connectors.

Under normal operating conditions, the Shack-Hartmann wavefront sensor does not need any service. It is recommended that the dust cover be screwed on whenever the wavefront sensor is not in use. Remove dust in the instruments entrance aperture with oil-free compressed air. There is no need to recalibrate the wavefront sensors after a period of time.

Do not stick anything into the aperture at the front of the Wavefront Sensor! You may damage the microlens array because there is no glass covering in front of it.

10.1. Service

Only trained Thorlabs personnel should service the system. Please contact techsupport@thorlabs.com.

10.2. Accessories and Customization

Any modifications or servicing done by unqualified personnel renders the warranty null and void, leaving Thorlabs free of liability. Please contact Thorlabs for questions on customization.

Chapter 11 Specifications

Item #	AOK5(/M) and AOKWT1(/M)
Boston Micromachines Deformable Mirror	
Deformable Mirror Type	Multi-DM
Deformable Mirror Item #	DM140A-35-P01
Actuator Array	12 x 12
Actuator Count	140
Actuator Stroke	3.5 µm
Actuator Pitch	400 µm
Clear Aperture	4.4 mm x 4.4 mm
Mirror Coating	Protected Silver
AR-Coated Window Wavelength Range	400 - 1100 nm[1]
Surface Quality	<30 nm RMS
Frame Rate	8 kHz (34 kHz Burst)
Average Step Size	<1 nm
Inter-Actuator Coupling, CDM[2]	13%
Head Dimensions	Ø2" x 0.89" (Ø50.8 mm x 22.5 mm)
Computer Interface	USB 2.0

[1] The mirrors are protected by a 6° wedge that is AR coated for the 400 - 1100 nm range.
[2] Continuous Deformable Mirror

Item #	AOK8(/M), AOKWT1(/M)
Thorlabs' Deformable Mirror	
Deformable Mirror Type	Piezoelectric DM
Deformable Mirror Item #	DMH40(/M)-P01
Actuator Array	40 Piezoceramic Disk Segments in a **Circular Keystone Array** (Elements 1 - 24 Inside Pupil Diameter, Elements 25 - 40 Outside Pupil Diameter)
Actuator Stroke[3]	Defocus: ±17.6 µm Astigmatism: ±18.4 µm Coma: ±6.8 µm Trefoil: ±6.5 µm Tetrafoil: ±5.7 µm Secondary Astigmatism: ±3.0 µm Third Order Spherical Aberration: ±2.7 µm
Clear Aperture	Ø17.0 mm
Pupil Diameter	Ø14 mm[4]
Mirror Coating	Protected Silver
Mirror Wavelength Range	450 nm - 2 µm with >97.5% R_{avg} 2 - 20 µm with >96% R_{avg}
Surface Flatness (RMS)	200 nm (Defocus Term Actively Flattened)
Hysteresis	20% Typical, 25% Max
Fill Factor	100%
Response Time	0.5 ms (Full Stroke) Mirror Response Time
Pattern Update Rate (Max)	4.0 kHz via USB 2.0 (Over Entire Voltage Range)
Head Dimensions	64.0 mm x 60.0 mm x 30.9 mm (2.52" x 2.36" x 1.22")
Computer Interface	USB 2.0

[3] Max Peak-to-Valley (PV) stroke at mirror surface within the 14.0 mm pupil diameter. The wavefront amplitudes are twice as high. The defocus range may have a maximum asymmetry of 30%. Max correction for this aberration assuming that no other aberrations are corrected for at the same time. When more than one type of aberration is corrected for simultaneously, these numbers will decrease.

[4] Maximum usable beam diameter is limited to the optical aperture: a wider beam will be truncated. The optical aperture diameter is wider than the pupil diameter to aid in maintaining beam quality and performing wavefront corrections at the pupil border. The pupil diameter is related to the normalized Zernike diameter: when using a wavefront sensor and deformable mirror together, a beam expander must be used to ensure that the pupil diameters of both devices are optically aligned.

Item #	AOK5(/M), AOK8(/M), AOKWT1(/M)
Thorlabs' WFS20-5C(/M) Shack-Hartmann Wavefront Sensors[5]	
Wavefront Sensor Item #	WFS20-5C(/M)
Sensor Type	CMOS
Wavelength Range	300 - 1100 nm
Frame Rate	880 fps
Camera Resolution (Max)	1440 x 1080 Pixels (Selectable)
Pixel Size	5.0 µm x 5.0 µm
Number of Lenslets (Max)	47 x 35
Lenslet Pitch	150 µm
Lenslet Diameter	Ø140 µm
Effective Focal Length	4.1 mm
Aperture Size	7.20 mm x 5.40 mm
Wavelength Sensitivity	λ/100 rms (@ 633 nm)
Wavefront Dynamic Range	>100λ (@ 633 nm)
Exposure Range	4 µs - 83.3 ms
Image Digitization	8 bit
Optical Input Connector	C-Mount
Physical Size (H x W x D)	46.0 mm x 56.0 mm x 33.1 mm (1.81" x 2.20" x 1.30")
Power Supply	External; 12 V DC, 1.5 A
Warm-up Time for Rated Accuracy	15 min
Operating and Storage Temp	5 to 35 °C (Operating) / -40 to 70 °C (Storage)

[5] *All technical data is specified at 23 ± 5 °C and 45 ± 15% relative humidity (non-condensing).*

11.1. Packing List

Please refer to the packing list below to ensure that the system is complete. Use only original parts. If any item is missing or damaged, contact Thorlabs for assistance.

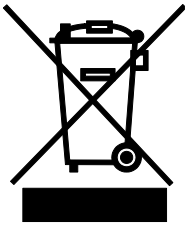
AOK5 Components	Quantity
Adaptive Optics Operating Manual and Quickstart Guide	1 ea.
Preassembled Cage Sections 1, 2, & 4	1 ea.
BMC's Deformable Mirror (multi DM) and Driver Module	1 ea.
Components to Mount DM:	
RS1.5P8 (RS38P4/M) [1], RSH2(/M) [1], PF125B [1], KS2D [1], and Screws	-
Fast Shack-Hartmann (WFS20-5C(/M)) with Dust Cover	1
Components to Mount the Wavefront Sensor:	
KM100WFS, TR2 (TR50/M), UPH2 (UPH50/M), SM1A9, NE10A and NE20A	1 ea.
Alignment Disk Assembly Components:	
SM1A7, TR2 (TR50/M), LMR1(/M), and UPH2 (UPH50/M)	1 ea.
Beam Splitter Assembly Components:	
BP108, KM100BP, SH85025-1, TR2 (TR50/M), and UPH2 (UPH50/M)	1 ea.
CPA1	3
CD-ROM for Shack-Hartmann wavefront sensor, which includes the required driver and application software	1
USB containing the Adaptive Optics Toolkit software and Operating Manual	1
USB 2.0 High Speed Cable USB A to Mini USB B, 1.5 m	2

AOK8 Components	Quantity
Adaptive Optics Operating Manual and Quickstart Guide	1 ea.
Preassembled Cage Sections 1, 2, & 4	1 ea.
Thorlabs Piezoelectric Deformable Mirror	1 ea.
Components to Mount DM:	
RS1.5P8 (RS38P4/M) [1], RSH2(/M) [1], PF125B [1], KS2D [1], and Screws	-
Fast Shack-Hartmann (WFS20-5C(/M)) with Dust Cover	1
Components to Mount the Wavefront Sensor:	
KM100WFS, TR2 (TR50/M), UPH2 (UPH50/M), SM1A9, NE10A and NE20A	1 ea.
Alignment Disk Assembly Components:	
SM1A7, TR1.5 (TR40/M), LMR1(/M), and UPH1.5 (UPH40/M)	1 ea.
Beam Splitter Assembly Components:	
BP108, KM100BP, SH85025-1, TR2 (TR50/M), and UPH2 (UPH50/M)	1 ea.
CPA1	3
CD-ROM for Shack-Hartmann wavefront sensor, which includes the required driver and application software	1
USB containing the Adaptive Optics Toolkit software and Operating Manual	1
USB 2.0 High Speed Cable USB A to Mini USB B, 1.5 m	2

AOKWT1 Components	Quantity
Adaptive Optics Operating Manual and Quickstart Guide	1 ea.
Preassembled Cage Sections 1, 2, 4, & 6	1 ea.
BMC's Deformable Mirror (multi DM) and Driver Module	1 ea.
Components to Mount DM:	
RS1.5P8 (RS38P4/M) [1], RSH2(/M) [1], PF125B [1], KS2D [1], and Screws	-
Thorlabs Piezoelectric Deformable Mirror	1 ea.
Components to Mount DM:	
RS1.5P8 (RS38P4/M) [1], RSH2(/M) [1], PF125B [1], KS2D [1], and Screws	-
Fast Shack-Hartmann (WFS20-5C(/M)) with Dust Cover	1
Components to Mount the Wavefront Sensor:	
KM200PM(/M) [1], AE8E25ES (AE4M6MS) [1], XRN-YZ(/M) [1], XRN-B1(/M) [1], XRN25P(/M) [3], SM1A9 [1], CL5 [1], NE10A [1], and NE20A [1]	-
Alignment Disk Assembly Components:	
SM1A7, TR1.5 (TR40/M), LMR1(/M), and UPH1.5 (UPH40/M)	1 ea.
Beam Splitter Assembly Components:	
BSN10, KM100, TR2 (TR50/M), and UPH2 (UPH50/M)	1 ea.
CPA1	3
CD-ROM for Shack-Hartmann wavefront sensor, which includes the required driver and application software	1
USB containing the Adaptive Optics Toolkit software and Operating Manual	1
USB 2.0 High Speed Cable USB A to Mini USB B, 1.5 m	2

Chapter 12 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return “end of life” units without incurring disposal charges.



- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out “wheelie bin” logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated

As the WEEE directive applies to self-contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e. g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB’s, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

Waste Treatment is Your Own Responsibility

If you do not return an “end of life” unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

Chapter 13 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at **www.thorlabs.com/contact** for our most up-to-date contact information.



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